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RESEARCH ON THE BINARY IRON-NICKEL ALLOYS WITH 20 TO 25 PERCENT NICKEL

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AIR FORCE MATERIALS LABORATORY
RESEARCH AND TECHNOLOGY DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

Project No. 1(8-7381), Task No. 738103

(Prepared under Contract No. AF 33(616)-8018 by
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FOREWORD

This report was prepared by Wright Aeronautical Division, Curtiss-Wright Corporation under U.S.A.F. Contract No. AF 33(616)-8018. This contract was initiated under Project No. 1(8-7381), Task No. 73812. The work was administered under the direction of the Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division, with Mr. H. Zoeller acting as Project Engineer.

This report covers work conducted from March 1, 1961 to September 30, 1962.

The scope of the program required the efforts and support of a team of engineers and technicians not only involving the Wright Aeronautical Division but also the staff of the Directorate of Materials and Processes, numerous steel suppliers and the International Nickel Company, who developed the alloys evaluated.

Specifically, the authors wish to acknowledge the interest, technical aid and recommendations offered by Mr. H. Zoeller and Lt. W. Payne of the Directorate of Materials and Processes. The technical information and background given by Messrs. R. Decker, C. Bieber and C. C. Clark, all of the International Nickel Company, were invaluable in the collection of data.

Many personnel at the Wright Aeronautical Division were involved in the scheduling, testing and collation of data. Specifically, the authors are indebted to Messrs. W. Taylor, O. A. Siede, M. Klein and M. Schwartz for their work in the above areas.

ABSTRACT

The physical metallurgy, mechanical properties and weld properties of the binary iron-nickel base alloys designated as Maraging Steels are presented in this final engineering report. This work was performed under U.S.A.F. Contract No. AF 33(616)-8018, "Research on Binary Iron-Nickel Base Alloys."

The primary data obtained during the program consisted of sheet and bar tensile properties as a function of various heat treatments and mill processing variables. Also determined were the fracture toughness parameters corresponding to strength levels produced by the various conditions mentioned above.

Secondary data generated included elevated temperature tensile properties, billet and forging properties, room temperature fatigue properties and Charpy impact strengths at cryogenic temperatures.

Included as a portion of the work was the selection of the most promising alloy for evaluation of biaxial strength. The biaxial strengths of burst tested 18% nickel (300 KSI) alloy using 6-inch diameter test cylinders ranged from 310 to 349 KSI. Biaxial gains as high as 17.5% were measured.

The results of the mechanical properties evaluation indicated that the best combination of fracture toughness and yield strength were offered by the 18% nickel alloys at both the 250 and 300 KSI strength levels.

A comparison of the alloys on the basis of weld tensile and fracture toughness properties indicate the 18% nickel alloys as exhibiting superior weldability. The 20 and 25% nickel alloys demonstrated heat affected zone embrittlement. The 25% nickel alloy exhibited the poorest weldability. Maximum weld yield strength joint efficiency and toughness were obtained in the 18% nickel (250 KSI) alloy.

This technical documentary report has been reviewed and is approved.

W. P. Conrardy

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1.0 INTRODUCTION

Aerospace design requirements demand the utilization of the highest practical strength-to-weight ratio. The strength level at which materials are applied with confidence is, however, restricted by an additional requirement. This requirement is one of tolerance for small crack-like defects which can occur during fabrication, testing, storage or service. The implication is that, for greater reliability, a material must possess adequate resistance to further extension of defect size.

The stringent strength-to-weight ratio requirements imposed by the aerospace designer have provided impetus for the research and development of high strength and high toughness alloys. One of the most promising class of alloys developed by this effort is the precipitation hardened 18-25% nickel steels, designated "Maraging Alloys". These alloys, which resulted from the work of C. Bieber and R. Decker of the International Nickel Company were announced in late 1959. Extensive and rapid development has resulted since their release. The alloys are presently capable of developing very high strengths with correspondingly high fracture toughness or crack propagation resistance.

Aware of the potential of the Maraging Alloys, the Metallic Materials Section of the Applications Laboratory, Wright-Patterson Air Force Base initiated and promoted further development of the alloys for aerospace use.

This final report, under Contract AF 33(616)-8018 reviews the development and strengthening mechanism of precipitation hardened iron-nickel alloys. The effects of various heat treating parameters on the mechanical properties and fracture toughness have been studied in detail. Heat treating cycles have been thoroughly evaluated. Essentially, the program conducted by this Contractor under the auspices of the Air Force has verified and proved the aerospace capabilities of the Maraging Alloys.

authors

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2.0 SUMMARY

The properties generated under AF 33(616)-8018, "Research on Binary Iron-Nickel Base Alloys", are presented in this final engineering report.

One heat of each composition, for the following alloys, 18% Nickel (250 KSI), 18% Nickel (300 KSI), 20% Nickel and 25% Nickel were evaluated. All heats were vacuum arc melted.

A discussion of the physical metallurgy of the alloys and development of the four compositions studied in this program are presented in detail.

The primary data obtained during the program consisted of sheet and bar tensile properties as a function of various heat treatments and mill processing variables such as cold working and warm working. Also determined were the fracture toughness parameters corresponding to strength levels produced by the various conditions mentioned above. The primary data was supplemented by the concurrent evaluation of alloy weldability and weld properties.

Secondary data generated included elevated temperature tensile properties, billet and forging properties, room temperature fatigue properties and Charpy impact strength at cryogenic temperatures.

Included as a portion of the work was the selection of the most promising alloy for evaluation of biaxial strength. This work was performed on the 18% Nickel (300 KSI) alloy using small burst test cylinders. Both forged and machined, as well as shear spun cylinders were evaluated in the welded and unwelded condition.

The biaxial strengths of burst tested, 18% Nickel (300 KSI) alloy cylinders were considered excellent. Burst strengths ranging from 310 KSI to 349 KSI representing biaxial gains as high as 17.5% were measured.

The major interest in the binary iron-nickel alloys was for critical aerospace applications such as solid rocket motor cases. The high tensile strengths in combination with excellent fracture toughness are extremely desirable for high strength-to-weight ratio applications. The results of this program have enabled the catagorization of the binary iron-nickel alloys on the basis of strength level and accompanying fracture toughness level. The catagorization was accomplished by graphically illustrating the above relationship for annealed material in Figure 1 and cold worked material in Figure 2. The graphic illustrations show that the order of alloy performance based upon strength and toughness is as follows.

The 25% Nickel produced the lowest strength levels for comparable fracture toughness. Consequently, the 20% Nickel alloy was superior to the 25% Nickel alloy. The 18% Nickel alloys (250 and 300 KSI) were vastly superior to either the 20% or 25% Nickel alloys relative to strength and toughness. A choice between the two 18% Nickel alloys was difficult to make since, the major difference between the alloys is the expected strength level differential. Both exhibit excellent strength and high toughness. Any choice between the two can only be made based upon the required design strength for a particular application.

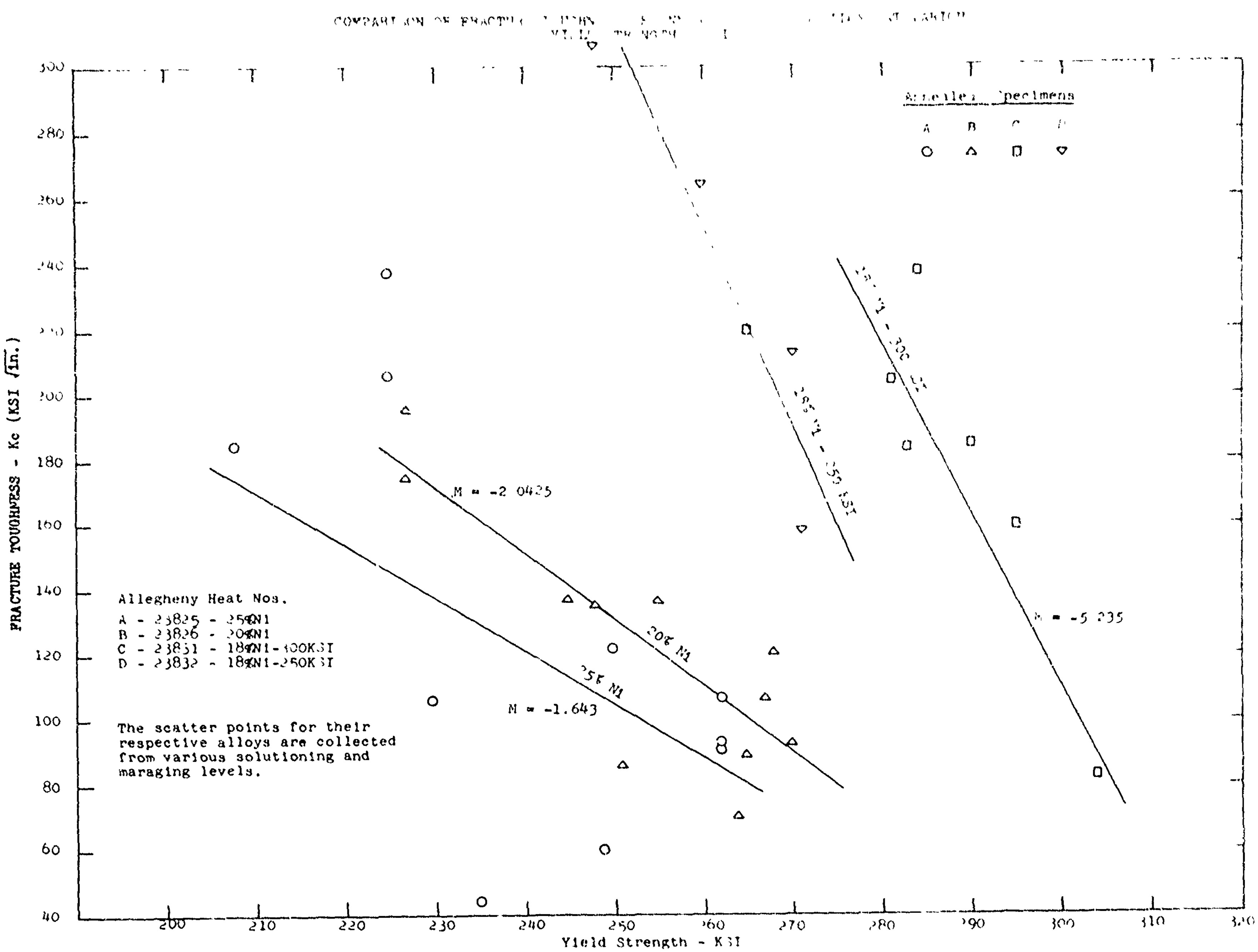
The work scope of the welding phase of the binary iron-nickel alloy program was limited to evaluation of gas, tungsten-arc (TIG) welded sheet. Weldability studies made in this investigation were directed toward determination of weld and heat affected zone soundness, and tensile strength properties for the four alloys of interest. Also, the potential of several available filler wires were compared on the basis of weld strength and fracture toughness. Each alloy was tested in two material conditions, solution heat treated and cold worked, in 0.140" thick sheet. In addition, for each alloy testing was also done on 0.070" thick solution heat treated material.

Final weld evaluations were made using heat treatments found to provide unwelded sheet with the best combinations of strength and toughness properties. Selection was determined on the basis of test results obtained for each alloy in the concurrent base material investigation.

Suitable, conventional TIG welding procedures were established in preliminary weld studies which consistently produced sound, ductile welds in all combinations of alloy, material condition and filler wire investigated. In all cases examined, welds and heat-affected-zones were free of defects and embrittlement as determined by inspection and bend testing. This level of quality was achieved without benefit of any "preheat-interpass-postheat" weld thermal cycle.

A comparison of the four nickel alloys on the basis of weld tensile and fracture toughness properties is presented in Figure 3. The results illustrate the relative performance of the 18%, 20% and 25% nickel alloys. Using heat treatments required to obtain maximum balance of strength and toughness in unwelded sheet, these materials exhibited superior weldability as determined by both strength and soundness. The 20% nickel alloy demonstrated a sensitivity to heat affected zone in embrittlement in welded 0.070" sheet after aging, whereas the welded 25% nickel alloy exhibited a similar behavior in both sheet thickness.

The 25% nickel alloy exhibited the lowest level of weldability of the four alloys investigated. Exclusive of tests on 0.070" sheet, weldability of the 20% nickel alloy compared favorably with that of the 18% nickel alloys. Maximum weld yield strength joint efficiency and toughness was obtained in the 18% nickel (250 KSI) alloy.



FRACTURE TOUGHNESS - Kc (KSI $\sqrt{in.}$)
Yield Strength - KSI
Allegheny Heat Nos.
A - 23825 - 25%Ni
B - 23826 - 20%Ni
C - 23831 - 18%Ni-300KSI
D - 23832 - 18%Ni-250KSI
The scatter points for their respective alloys are collected from various solutioning and maraging levels.
M = -2.0425
M = -1.643
M = -5.235
20% Ni
25% Ni
A B C D

Figure 1

5

COMPARISON OF FRACTURE TOUGHNESS OF COLD WORKED, MARAGING ALLOYS
AT VARIOUS YIELD STRENGTH LEVELS*

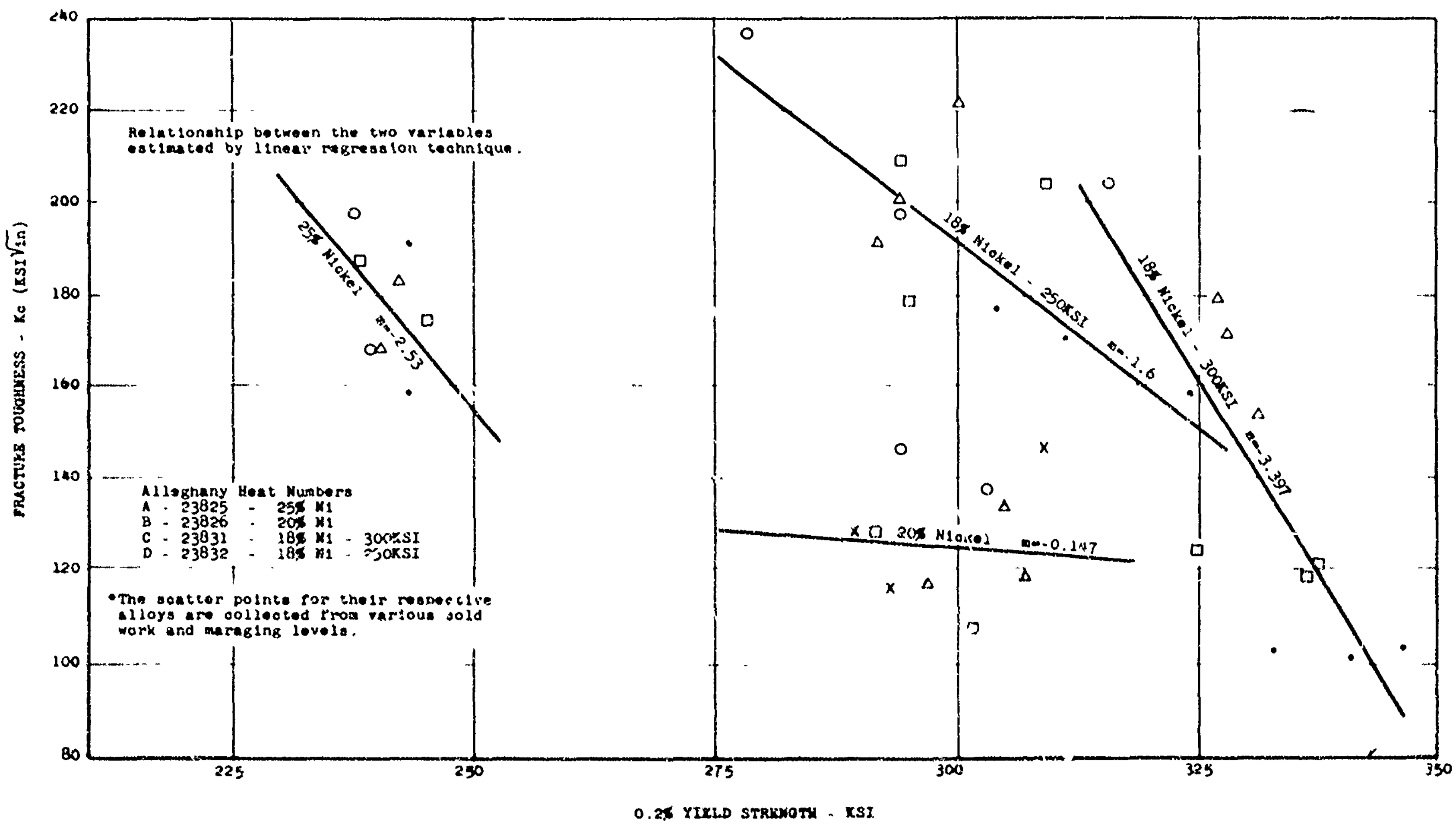


Figure 2

COMPARISON OF TRANSVERSE WELD AND FRACTURE TOUGHNESS PROPERTIES

18, 20 and 25% NICKEL ALLOYS

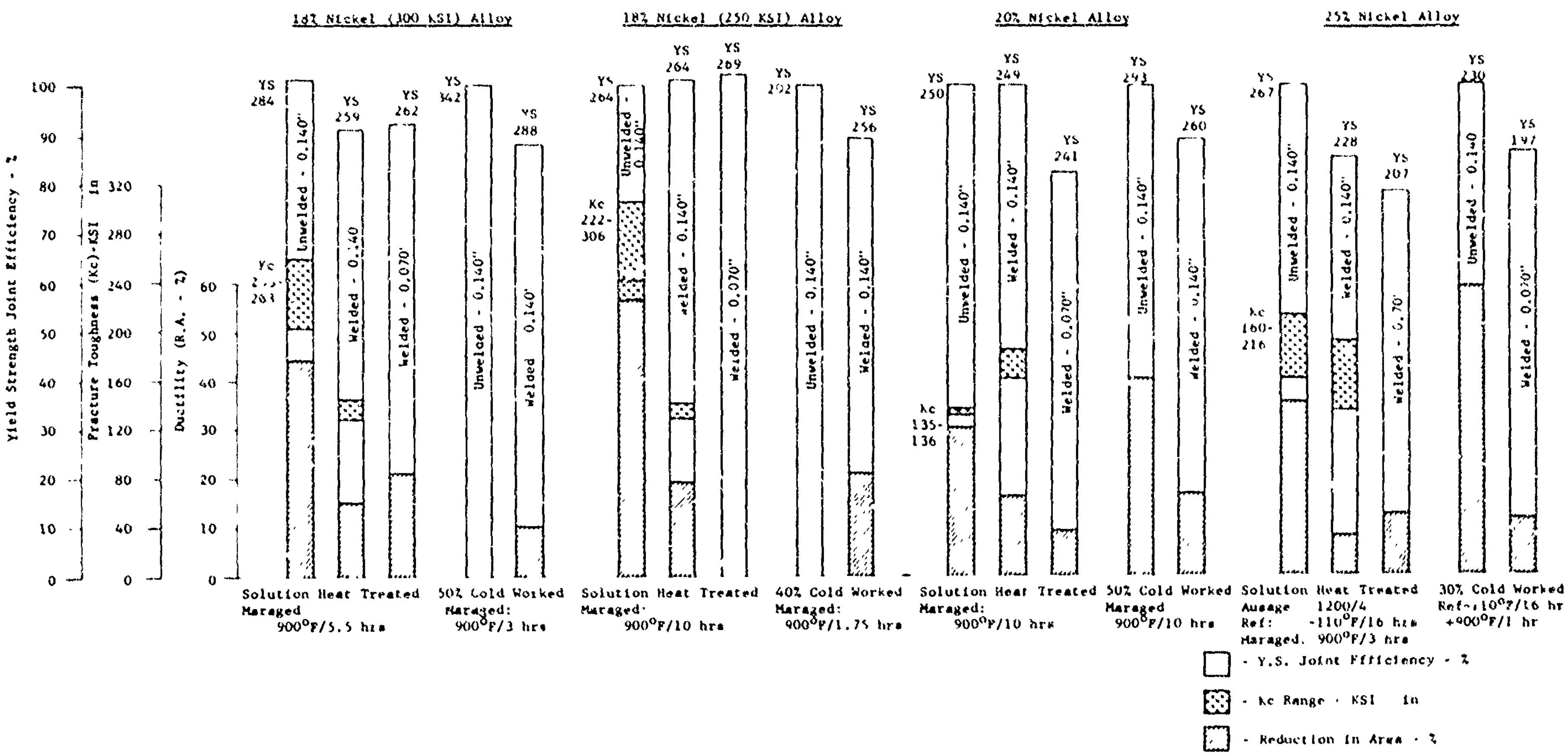


Figure 3

3.0 18% NICKEL ALLOY

The main objectives of the development program on the binary iron-nickel base alloys were to:

1. Review the development of commercial, precipitation strengthened iron-nickel alloys.
2. Study the effects of various heat treating parameters on mechanical properties and fracture toughness.
3. Develop maximum response heat treating cycles for the compositions studied in the program.
4. Compare the studied heats of the various alloys on the basis of crack propagation resistance at comparable yield strength levels.
5. Evaluate TIG Welding techniques.
6. Evaluate stress corrosion and general corrosion properties of the alloys.
7. Evaluate the biaxial strength of the most promising alloy by conducting subscale burst tests.

The compositions, processing history, test procedure and preliminary results of the alloys studied under this contract are discussed in the following section.

3.1 Experimental Procedures

3.1.1 Materials

The material requirements necessitated the melting of a 5000 pound heat of each of the four compositions (104). Because of the relatively small size of the heats, the melting was accomplished in an air induction furnace. High priority raw materials such as electrolytic iron, electrolytic nickel, and vacuum melted ferro-titanium were used in order to keep residual elements within the desired limits. The air melt of each heat was cast in the form of electrodes (16" diameter x 2200 lb) for consumable vacuum melting.

The compositions of the four heats, the number of which are given below, are shown in Table 1.

(a) 18% nickel alloy (250 KSI) - Heat No. 23832
(b) 18% nickel alloy (300 KSI) - Heat No. 23831
(c) 20% nickel alloy - Heat No. 23826
(c) 25% nickel alloy - Heat No. 23825

It should be noted from the presented table that the compositions of the hardening elements in the respective heats are toward the high side of the specification range.

3.1.2 Processing History

The consumable vacuum melted ingots of all the heats were soaked for 2 hours at 2300°F for homogenization prior to any further working. The homogenized ingots were, then, processed into thick sections, bar, and sheet stock in the various conditions as per the steps shown below.

3.1.2.1 Sheet Stock

The homogenized ingots were hot forged at 2100°F into slabs which were approximately 2½" x 16" x 100". The slabs were hot stripped on a 6-stand tandem mill, rolling to a nominal .375" gage by the slab width which was nominally 18". The sheet bars produced (.375" x 18" x length) were processed into the various conditions as follows:

1. Warm Work

   Sheet bars were heated at 1850°F for 1 hour. The sheet bars were rolled to .145" gage. The 20% nickel alloy was rolled in one direction only and the two 18% nickel-cobalt-molybdenum steels were rolled to 36" in length, turned and rolled to .145" gage. Six to eight passes were required to reduce to gage. Sheets were pickled and spot conditioned as necessary. Reheating was done as specified using 1600°F, 1400°F, and 1200°F as starting temperatures. The sheets were brought to temperature in one hour and rolled to .115" gage (20% reduction) in one or two passes only. Rolling was done in the length direction only. All sheets were acid pickled prior to shipment.

2. Cold Work

   Individual sheet bars were cut from the .375" gage hot rolled strip. The sheet bars were muffle annealed at 1500°F for 40 minutes and air cooled. All sheet bars were conditioned by grinding the entire surface in preparation for the following cold rolling steps:

(a) The "as-rolled" material was cold rolled in one direction only to the final, required gage (0.115" thick) followed by some shearing and inspection.

(b) The respective cold worked materials (20,30,40,50 and 70% reduction) were cold rolled to the intermediate stages and annealed at 1500°F for 15 minutes, air cooled, and acid pickled. This was followed by cold rolling to finish gage (0.115" thick) and by shearing and inspection.

3.1.2.2 Bar Stock

As in sheet stock, the bar stock was fabricated from the homogenized ingots into the 5/8" diameter bar stock in the various conditions as per the following steps:

(a) Warm Worked

$1\frac{1}{2}$" diameter stock was soaked at 2000°F for 1 hour and subjected to an initial swaging operation. The bars were then swaged to 5/8" diameter bar stock (with approximately 20% reduction of the original area) at warm working temperatures of 1200°F, 1400°F, and 1600°F respectively.

(b) "As Swaged"

The bar stock was initially swaged after soaking for 1 hour at 2000°F and was then finished between 1200°F and 1500°F.

(c) Cold Worked

The bar stock was soaked at 1500°F for 1 hour and swaged from $1\frac{1}{2}$" diameter to 1.17" diameter. It was then cold drawn in approximately 8% increments to size with total reductions of 70%, 50%, 40%, 30% and 20% respectively.

3.1.2.3 Thick sections

The thick sections were annealed at 1700°F and upset to the following heights and ratios.

Upset Height	Corresponding Reduction Ratio
5 1/3"	1½ : 1
4"	2 : 1
2 2/3"	3 : 1
2"	4 : 1
1 1/3"	6 : 1

3.1.3 Specimen Testing

Hardness tests were used as a preliminary tool for the selection of various levels of the heat-treating parameters. Duplicate hardness blocks, (½" x ½"), sheared from the sheet stock of four heats, were heat treated at several solutioning and maraging temperatures and times. The hardness data was analyzed and, from the analysis, promising levels of heat-treating were selected for further evaluation by tensile and fracture toughness tests.

Sheet stock (0.115" thickness) was used for studying the effect of various heat treating parameters on the mechanical properties and fracture toughness of the various alloys in different conditions. Longitudinal (parallel to the direction of rolling) and transverse (normal to the direction of rolling) tensile and crack propagation (G_c) specimen blanks were sheared from the different sheet stocks.

Standard sheet tensile specimens **(Figure 4)** were machined from the blanks and the specimens tested in the various heat treated conditions using standard ASTM testing procedures on a 2" gage length.

The fracture toughness of the various materials were evaluated by using a centrally notched, fatigue cracked specimen. The design of the crack propagation specimen is shown in **Figure 5**. The transverse slot in the specimen, with a small root radius, was machined and hairline cracks (root radius less than .001 in) were formed at the end of the slot by fatigue stressing the specimen in a sheet bending fatigue machine. All the test procedures recommended by the ASTM committee (Ref. 116) based on the Irwin criterion, were followed with one exception: Ink staining to estimate the extent of slow crack growth was abandoned because of the splashing of the ink on the fracture surface. Moreover, it was found in the early stages that the estimation of the slow crack growth from the triangular "porous torque" on the fracture surface corresponded closely to the estimate using ink staining. The fracture toughness parameters were calculated by an IBM 704 program.

The exceptional ductility of the maraging steels after certain heat treatments produced net section stress values higher than the materials yield strength. The K_c values calculated for these tests are, in the strict sense of fracture toughness theory, not valid. However, they do provide uniformity in data reporting as well as a rough measure of the materials toughness for comparative purposes.

Smooth bar data and high temperature data was collected on 0.252' diameter x 1" gage length tensiles. The critical fracture toughness parameters, $K_{1}C$, were estimated from round circumferentially-notched

tensile bars having a major diameter of .252" and a minor diameter of 0.178" and a notch radius of less than .001" ($K_t > 10$). The critical fracture parameters were estimated from the formula proposed by Irwin (117):

$$K_{1C} = 0.233 \sqrt{\pi}\, \sigma_n \sqrt{D}$$

where σ_n is the net-section stress

D is the diameter of the round bar

Instances were encountered where the notch to smooth tensile yield strength ratio exceeded 1.10. In reality, the results of tests exceeding the 1.10 ratio are invalid in interpreting the K_{1c} value accurately.

The K_{1c} values are reported only for data comparison, since they offer a reasonable method for evaluating the entire set of results.

Impact, smooth, and notched fatigue properties were evaluated by machining Charpy and R.R. Moore (rotating bear) specimens from the bar stock and testing them under the standard testing procedures. The 90% probability of survival curves were drawn for the endurance limit for various materials by estimating the standard deviation in the endurance region.

3.1.4 Preliminary Evaluation on Chemistry Variance

Before starting the detailed work of the program, a preliminary evaluation was made to study the effect of chemistry variance, from the upper to the lower limits, on the mechanical properties of an 18% nickel alloy (300 KSI).

Two sixty (60) pound laboratory heats (Heat Nos. 7C-056 & 7C-057) were made by Allegheny-Ludlum for this investigation. Table 5.1.2 gives the target compositions and the actual heat analyses for the two heats. The melting methods, processing history, and the type of specimens used in this preliminary evaluation are summarized in Table 3. It should be noted that an edge notch G_c specimen was only used in this preliminary evaluation and that, in the remainder of this program, centrally notched, fatigue cracked specimens were used for evaluating crack propagation resistance. The preliminary mechanical properties data and bar and sheet stock made from heats 7C056 and 7C057 are presented in Tables 7 **and 8 respectively.**

Inspection of the data on the low alloy heat, 7C056, revealed that, on sheet material, although a slight drop in strength occurred when the sheet was annealed at 1500°F, the resultant ductility was unaffected while toughness was substantially increased. Essentially, eliminating the annealing cycle in order to increase strength apparently resulted in a loss of toughness for this heat. The toughness properties on cold worked material revealed that 30% cold work and 50% cold work appear to bracket a peak reduction value.

The bar data on Heat 7C056 revealed little, if any, difference in strength or toughness properties as a function of annealing prior to aging. Specimen size and geometry may be insensitive to minor structural changes induced by the anneal.

Table 5 reports the data obtained on the high chemistry heat, 7C057. The data on this heat indicated that the increased cobalt, molybdenum and titanium raised the strength by approximately 40,000 psi. A check of this value, made by ascertaining the relative strengthening effects caused by the increased amount of the three elements verified this approximate increase. The degree of cold work appears to effect a similar behavior on toughness as experienced with the low alloy heat. The toughness of the 30% cold worked material is noticeably higher as was the 30% cold worked material for heat 7C056.

Bar data obtained on this heat showed strength and toughness behavior similar to the sheet material. Again the annealed material exhibited a lower toughness.

This preliminary evaluation indicates that alloy composition, although within the range of the specification, has a very significant effect on the mechanical and fracture properties of the alloy.

3.1.5 Experimental Procedures - Welding

Wherever possible the welding test program was made to parallel that of the base material. Specimen types, testing procedures, heat treatments, etc. were duplicated where feasible in order to make meaningful comparisons between weld and base material data.

3.1.5.1 Materials Studied

Base Materials

All four iron-nickel alloys were evaluated in the welding investigation of this program. The materials used were from the same heats described in Section 3 and listed in Table 1. Each alloy was welded in both the solution heat treated (1500°F/1 hr.) and cold worked conditions in 0.140" thick sheet. A limited amount of work was also done on solution heat treated 0.070" thick sheet.

Filler Materials

All filler materials used were prepared from vacuum-melted heats and drawn to 0.062" diameter for welding. The filler wires originally selected for evaluation on the group I alloys (18% nickel) are given in Table 6. At an advanced stage of the program, an additional

filler wire was obtained from International Nickel Co., Inc. for evaluation. This wire, Table 7, is within compositional limits for their current cast alloy. It should be noted that this alloy, unlike the early cast version (Table 6), is copper-free alloy with increased cobalt and is reported to have improved notched toughness. All four of the filler wires were tested on the 250 KSI alloy, while all but the lower strength 250 KSI filler wire were tested on the 300 KSI alloy. The matching 250 and 300 KSI base metal fillers were also tested on the 20 and 25% nickel alloys.

Filler wire compositions of modified 20% nickel alloy selected for evaluation and tested on Group II alloys are given on Table 8. These compositions, low nickel (18%) with and without molybdenum, and 20% nickel with molybdenum, are representative of those previously evaluated and recommended by INCO.

3.1.5.2 Welding Conditions and Procedures

General

The gas, tungsten-arc (TIG) welding process was used exclusively in this investigation. Weld settings and joint design which served as standards for the preparation of weld test panels are listed in Figure 6. Suitable weld settings capable of producing sound welds in each alloy were established primarily on the basis of penetration studies in which several weld variables were examined. Wherever possible, consideration was also given to developing an overall procedure which would be representative of current state of the art rocket motor case fabrication, without sacrifice to weld quality, particularly in the selection of certain set variables.

Welding Conditions

Selection of welding current, voltage, travel speed and wire travel speed was based primarily on the results of penetration studies, discussed in section 3.1.6. These settings are listed in Figure 6.

Set process variables selected for the welding program are also included in Figure 6. A joint design of 70° included angle with a land of 50% of wall thickness was used exclusively for both material thicknesses tested. This joint design was selected as being both simple and representative of current rocket motor case fabrication. A standard wire diameter of 0.062" was used in all tests. Helium and Argon gases were used for the fusion and filler passes respectively. A "preheat-interpass-postheat" weld thermal cycle was not employed in this program. All welds were made using a 5/32" diameter thoriated tungsten electrode and copper back-up material.

Weld Panel Preparation

Weld test panels, approximately 12" wide x 9" length, were prepared to provide the required test specimens. Weld wire and sheet were both thoroughly cleaned prior to welding. The 0.140" thick material was welded in two passes, the second with filler wire. A single pass with filler wire added was used to weld the 0.070" material.

3.1.5.3 Specimen Testing

Hardness tests were used to determine the relative response of weld deposits to heat treatment. In addition, hardness was used to detect changes experienced in base material heat-affected zones due to welding.

Vertical hardness surveys taken along the weld centerline, Figure 7, were used to evaluate weld deposits of all of the filler wires investigated. Weld heat-affected-zones of each alloy in both solution heat treated and cold worked conditions were evaluated on the basis of horizontal weld surveys (Figure 7). All surveys taken compared as-welded versus aged hardness properties.

Transverse weld guided-face bend tests were made to compare the relative as-welded ductility of the various filler materials evaluated. They also served to determine whether any embrittled areas were present in the weld heat affected zone prior to aging. The standard test specimen used is shown in Figure 8. Specimens were tested to obtain a full bend using standard ASTM testing procedures. Test data were analyzed on the basis of minimum bend die radius.

The various combinations of filler wires, alloys, and material conditions were evaluated by transverse tensile tests. In these tests, sheet rolling direction was parallel to the test direction and normal to the direction of the weld. The 18% nickel alloys (250 and 300 KSI) were tested more extensively because of the greater interest in these materials. Additional transverse tensile tests were made on welds with the sheet rolling direction normal to the test direction (parallel to the weld). Longitudinal weld tests were also made on the 18% nickel alloys.

The same standard sheet tensile specimen (Figure 4) and testing procedures described for base material testing in Section 3 were used in transverse weld tests. The longitudinal weld test specimen used is shown on Figure 9.

The various combinations of filler materials and base materials investigated in the weld program were tested in two heat treatment conditions. Preliminary weld tensile tests were made using a heat treatment which was selected on the basis of the best available data for each of the four alloys. Additional weld tensile tests were made using heat treatments developed for the alloy heats investigated in this program. These heat treatments provided what appeared to the best balance of properties as indicated by analysis of yield strength and fracture toughness test data obtained for each alloy. Table 9 lists all of the heat treatments used in weld tests. The heat Treatments used in preliminary tests are listed first for each combination of alloy and condition. The base material tensile strengths obtained with these treatments are also included in Table 9. These data were used to calculate weld joint efficiencies presented in later sections.

Fracture toughness of welds was evaluated using the same specimen used for base materials. As shown in Figure 5 the fatigue cracked notch was centered in the weld. Notch initiation method and test procedure were previously described for base materials in Section 3. Weld fracture toughness properties were determined using only the final heat treatment listed in Table 9.

3.1.6 Preliminary Evaluations-Welding

3.1.6.1 Penetration Studies

Penetration studies were made on each of the three basic iron-nickel alloys prior to the fabrication of welded test panels. The effects of current, voltage, travel speed and filler wire speed on penetration were examined.

The results of penetration studies on the 18 and 20% nickel alloys (0.140" sheet) are illustrated in Figures 10 to 14. As indicated, these two alloy types demonstrated similar behavior for all variables examined. Tests made on the 25% nickel alloy on 0.070" sheet are shown in Figures 15 to 17.

3.1.6.2 Weld Quality

The test welds produced in the various combinations of base and filler materials were inspected by both dye penetrant and X-ray methods. All were found to be of excellent quality - free of cracking in both weld and heat-affected zone. Welds also demonstrated freedom from porosity. A slight sensitivity to edge porosity was noted in several preliminary 18% nickel alloy welds; however, this was eliminated by reducing weld travel speed.

3.1.6.3 Metallographic Evaluation

Welds and base material heat-affected-zones were evaluated metallographically. Examination was made to determine what heat affected zone structural changes occurred as well as to study the nature of weld microstructures. All examinations were made at 500X. A photomicrograph of a typical transverse weld microspecimen used in this investigation is shown in Figure 18.

Group I Alloys

The 18% nickel alloy welds exhibit a duplex structure of predominantly martensite with small amounts of retained austenite after aging. Little difference was observed between the microstructures of the three filler wires deposits examined, Figure 19. The duplex structure is typical of the filler wire pass. The fusion pass is almost completely martensitic and any retained austenite islands are distributed randomly as opposed to the directional segregation exhibited in filler passes, Figure 19. This variation is associated with the rather gross columnar structure observed in the filler pass as compared to the equiaxed grain structure of the fusion pass as seen in Figure 18.

In Figure 20 and 21, the microstructure of the weld heat-affected-zone closest to the weld fusion line is compared against that of unaffected base material for 250 KSI material in solution heat treated and cold worked conditions. Severe grain growth characteristic of this zone was experienced in both material conditions.

A more extensive examination of the 18% nickel alloy heat-affected-zone is presented in Figures 22 and 23 for solution heat treated and cold worked 300 KSI alloy respectively. In these figures the weld heat-affected-zone is divided into several areas for purposes of clarification. Zone 1 represents that area subjected to maximum temperatures, e.g. 1600°F to fusion, accompanied by excessive grain growth. That portion of Zone 1 subjected to the highest temperatures are shown in the photomicrograph of the weld-base metal interface, Figure 22. The structure shown in Zone 2 is representative of that area exposed to an approximate temperature range of 1000°F to 1600°F. This area is subjected to partial resolution but no aging at the lower temperatures, and complete resolution but little or no grain growth at the higher temperatures. The area of the heat-affected zone subjected to aging temperatures is shown in Zone 3. Little or no difference is observed between the solution heat treated and cold worked materials wherever solution temperatures were exceeded (Zones 1 and 2), since the latter reverts to a solution treated structure.

Group II Alloys

The 20% nickel alloy weld microstructures, fusion pass, shown in Figure 24 and Figure 25, shows deposits made using different filler wires. Like the 18% nickel alloy welds, the fusion pass appears to be almost completely martensitic, while the filler wire deposits exhibit a duplex structure of predominantly martensite surrounding interdendritic, discontinuous stringers of austenite.

Weld-heat-affected-zone microstructures, Figures 26 and 27, experienced changes similar to those previously described for the 18% nickel alloys. Definition of various zones is very nearly identical since solution and aging temperature are similar for the two alloys.

Figures 28 and 29 show weld microstructures for the 25% nickel alloy. The fusion pass, Figure 28, appears to contain greater amounts of retained austenite than similar areas in either the 18 or 20% nickel alloys. Filler wire deposits, Figure 29, all of which are basically 18 and 20% nickel compositions, are similar in structure to those previously shown in the 20% nickel alloy welds, Figure 25.

The heat-affected zones for 25% nickel alloy are shown in Figures 30, solution heat treated, and 31, cold worked. As discussed in a previous section, the heat treatment of the 25% nickel alloy differs from that of the lower nickel types. It does not transform directly to martensite from solution temperature, but requires an intermediate ausaging treatment at 1200 to 1300°F to allow transformation. The solution heat treatment temperature is basically the same in all three alloys.

In Figures 30 and 31, only zone 1 is similar to that previously shown for the lower nickel alloy types in that it experienced excessive grain growth. It is, however, austenitic in structure rather than martensitic in the as-welded condition. Zone 2 represents the area which undergoes solution but does not experience grain growth. The heat-affected-zone area which is exposed to ausaging temperatures during welding is shown in Zone 3.

3.1.6.4 Bend Tests

Group I Alloys

The results of weld bend tests made on Group I Alloys are listed in Tables 10 and 11 for 250 and 300 KSI types respectively. All fillers evaluated on both alloys possessed good ductility as evidenced by the test data. On the basis of both sets of data on 0.140" sheet, no single filler wire demonstrated any outstanding superiority in the

bend tests. The best results were obtained with 300 KSI wire on 250 KSI sheet, which passed at minimum bend radius of 1 T. In general, all of the filler wires demonstrated superior bend properties in tests made on the 0.070" thick sheet. No evidence of weld heat affected zone embrittlement was observed in the bend specimens of either Group I Alloy.

Group II Alloys

Group II Alloy bend test results are given in Tables 12 and 13. Bend specimens from both 20 and 25% nickel alloy (0.140" thick sheet) made using the same filler wires exhibited a wide difference in bend ductility. Two of the filler wires (7C-058 and 7C-060) performed substantially better on the 25% nickel alloy. This variation was not evident in bend tests made on similar welds in 0.070" thick sheet. The filler wires evaluated exhibited equally good ductility on both alloys in 0.070"sheet. Heat affected zones in Group II alloy bend specimens were free of any embrittled areas.

3.2 18% Nickel Alloy (250 KSI)

The results of the effect of the various heat-treating parameters on the hardness, mechanical properties, and fracture toughness of 18% nickel alloy (250 KSI) in the various conditions are discussed in this section. In addition, the fracture toughness of the various conditions are compared in the final portion of the section.

3.2.1 Solution Annealed Condition

3.2.1.1 Effect of Solution and Maraging Parameters on Hardness

The "as-quenched" hardness response after solution annealing at various conditions is plotted in **Figure 32** and the hardness results reported in Table 14. The solutioning parameters have a more pronounced effect on the "as-quenched" hardness and the hardness drops significantly at solutioning temperatures above 1700°F. The hardness impressions show very small variations after the alloy is maraged for 3 hours at 900°F subsequent to solutioning and the maraged hardness did not indicate any consistent patterns. Solution temperature selections were made from the "as-quenched" hardness data. Temperatures of 1400, 1500, 1600 and 1700°F were selected for more extensive evaluation of sheet tensile data.

3. It correlates better with yield strength. Crack propagation resistance for a given material and condition, as measured by the Kc criterion, tended to decrease at higher strength levels.

4. In contrast to the critical driving force (G_c) criterion, Kc, is independent of modulus of elasticity. The calculated Kc values can be slightly more reliable since the modulus of elasticity for the iron-nickel alloys vary significantly among different specimens. The modulus of elasticity in these alloys is dependent upon the composition and to some extent on the heat treat condition.

5. Kc could be used as a yardstick for comparing the iron-nickel alloys with other high strength steels. Present indications, based on a large amount of data, suggest that a high strength steel for a rocket motor casing can be heat-treated to a yield strength level of 220 Ksi $\sqrt{\text{in.}}$ if it possesses a Kc value of 150 Ksi $\sqrt{\text{in.}}$ at the yield strength and if the undetectable flaws in the final inspection are less than .030 in.

Based on the above arguments, emphasis in this report is placed in evaluating the fracture toughness parameter Kc, at the different levels. However, other fracture toughness parameters have also been calculated and presented in the various tables.

The longitudinal and transverse toughness are compared at two solutioning temperature and time levels in Figures 37 and 38 respectively. The effect of solutioning on the fracture toughness is presented in Table 18. The longitudinal Kc value shows a sharp drop from 251.7 KSI $\sqrt{\text{in.}}$ to 157.5 KSI $\sqrt{\text{in.}}$ when the solutioning temperature is changed from 1500°F to 1400°F. Changing the holding time from ½ hour to 1 hour at 1500°F does not have any significant effect on the Kc value. The alloy exhibits excellent crack propagation resistance at both solutioning times.

3.2.1.4 Effect of Solution Annealing Temperature on Microstructure

The effect of the solution annealing temperature on the microstructure is shown in Figure 39. Solution treating at 1400°F does not completely homogenize the structure, and the effects of previous working are still apparent. At 1500°F the alloy is essentially homogeneous and the microstructure becomes progressively coarser with increasing temperature.

The heterogeneity and the indication of residual effects of working in the structure can probably explain the observed high strength and low

fracture toughness of specimens which are solution annealed at 1400°F.

3.2.1.5 Effect of Maraging Parameters on the Tensile Properties of Solution Annealed Alloy

From the solution anneal tensile and fracture toughness data, solution treating temperature and time for 1 hour and 1500°F were selected as the optimum parameters and were held constant in the determination of the effect of maraging conditions on the mechanical properties of solution annealed alloy.

Several longitudinal and transverse sheet tensile specimens were solution annealed at 1500°F for 1 hour, air quenched, and maraged under the following conditions which were selected from the hardness data:

(i) 850°, 900°, and 950°F respectively

(ii) one (1), three (3), and ten (10) hours at the respective maraging temperatures.

The longitudinal and transverse tensile properties of both the 18% nickel alloys are presented in Tables 19 and 20. The longitudinal and transverse yield strengths are plotted as a function of maraging temperatures in Figures 40 and 41.

The longitudinal and transverse yield strength response surfaces are plotted as a function of maraging time and temperature in Figures 42 and 43. It is clear from the presented surfaces that the yield strength responses are maximum when the alloy is maraged at 900°F for 10 hours.

3.2.1.6 Effect of Maraging on Fracture Toughness

The effect of the maraging parameters on the fracture toughness are shown in Table 21. Changing the maraging time from 3 to 10 hours at 900°F results in a slight drop of fracture toughness. However, the alloy still exhibits good fracture toughness in both the longitudinal (K_c = 213 KSI $\sqrt{\text{in.}}$) and transverse (K_c = 175 KSI $\sqrt{\text{in.}}$) directions. The higher yield strength response at the higher maraging level suggests that, whenever economic and other fracture mechanics considerations permit, the solution annealed 18% nickel alloy would be maraged at 900°F for 10 hours.

3.2.2 Cold Worked Condition

3.2.2.1 Effect of Cold Work on the Tensile Properties

In order to study the effect of the degree of cold working, longitudinal (parallel to the direction of rolling) and transverse (normal to the direction of rolling) specimens were machined from sheets cold worked 20, 30, 40, 50, and 70% reduction. All the specimens were maraged at 850°F and 900°F in order to evaluate the effect of maraging on the tensile properties of cold worked material. The time at the respective maraging temperatures was varied from 1 to 10 hours.

The results of effect of the cold work on the longitudinal and transverse tensile properties are given in Tables 22 and 23. The yield strengths in the two rolling directions are plotted as a function of percent cold work, at constant maraging temperatures in Figures 44 and 45. By plastically deforming the structure or, in other words, by increasing the dislocation density, the strength of martensite is increased significantly.

Due to the dislocation blocking mechanisms, the movement of dislocation seems to be greatly impeded in the cold worked structure and the alloy exhibits higher yield strength responses. It should be noted that the longitudinal yield strength of 324,000 psi, observed in 50% cold worked material, is significantly higher than the longitudinal yield strength (264,000 psi) of solution annealed condition.

3.2.2.2 Determination of Optimum Maraging Parameter and Cold Work

In order to analyze the data effectively and visualize the geometrical relations between the yield strength response and the various factors, the collected yield strength data is plotted as a function of percent cold work and Larson-Miller parameter in Figure 46. The maraging time and temperature were expressed in the form of the empirical Larson-Miller parameter,

$$P = {}^{\circ}R\ (20 + \log \text{hours}) \times 10^{-3}, \text{ since:}$$

(a) The mechanical properties of maraging steels seems to correlate well with the Larson-Miller parameter (110).

(b) Various combinations of time and temperature factor levels give corresponding values of yield strength.

(c) The model of response surface gives a vivid and accurate representation of all the factors of interest, namely, maraging time, maraging temperature, and cold work.

(d) It focuses attention on the levels of the factors without the distraction of representing the response in a further dimension.

The longitudinal yield strength response surface of 18% nickel alloy (250 KSI), as represented in Figure 46 shows several interesting features. The surface indicates that the optimum yield strength response is at the 50% cold work level and at 27.5 Larson-Miller parameter level (see the shaded area).

With increasing cold work, the slope of the yield strength surface is constant until the 40% cold work level. There is a slight increase in slope between the 40% and 50% cold work level and, then, the yield strength begins to drop slowly at the higher cold work levels.

As expected, the response surface shows a very sharp rise between a "P" of 26.2 to 27.2. The rise in response is gradual from a "P" of 27.2 and the maximum ridge is reached at the Larson-Miller parameter level of 27.5, i.e., equivalent to 10 hours at 850°F, or to 1.75 hours at 900°F; or to 0.32 hours at 950°F. At levels greater than a "P" of 27.5, the alloy's structure overages and/or reverts to austenite and there is a slight drop in the mechanical properties (110).

3.2.2.3 Effect of cold work on the fracture toughness

The effect of cold work on the longitudinal and transverse fracture toughness parameter, K_c, is shown in Figure 47. Table 24 gives the results of the other fracture toughness parameters. From the collected data, it is evident that:

(a) The K_c value drops quite sharply at the higher cold work levels. For instance, the longitudinal value drops from an average of 235 Ksi $\sqrt{in}$ at the 20% cold work level to about 145 at the 70% cold work level.

(b) At the same cold work level and heat treat condition, the transverse K_c is sharply lower than the longitudinal K_c value. For example, the transverse K_c for 50% cold work is only 90 Ksi $\sqrt{in.}$ and is considerably less than the longitudinal K_c (900°F/3 hrs) value of 170 Ksi $\sqrt{in.}$.

(c) At a given cold work level, the variation of maraging heat treatment has relatively little effect on the fracture toughness. The decrease in the fracture toughness is proportional to the increase in strength level. The relationship between the fracture toughness and the yield strength has been estimated by the linear regression techniques and are discussed in the last part of this section.

It is obvious that small amounts of cold work, i.e., amounts less than 30% reduction, do not have any radical effect on the longitudinal or transverse K_c value. However, the heavily cold worked material should only be used after giving careful consideration to the fracture mechanics of the system. The transverse K_c value of a 50% cold worked alloy is only about 90 Ksi $\sqrt{in.}$ at the 320,000 psi yield strength level.

3.2.3 Warm Worked Condition

3.2.3.1 Effect of Warm Work on the Tensile Properties

Longitudinal and transverse specimens were machined from sheets warm worked at 1200, 1400, and 1600°F. All the specimens were maraged at 850°F and 900°F in order to determine the effect of maraging on the tensile properties of warm worked material. The time at the respective maraging temperatures was again varied from 1 to 10 hours.

The tensile properties of warm worked 18% nickel alloys are given in Tables 25 and 26. The longitudinal yield strength properties are presented as a function of warm working temperature in Figures 48 and 49. In addition, the yield strength response surface is plotted as a function of warm working temperature and Larson-Miller parameter in Figure 50.

The yield strength surface response of the alloy in the warm worked condition, has the following distinct features:

1. The optimum yield strength responses are around the 1400°F warm working temperature level and at 28.56 Larson-Miller parameter level.

2. The yield strength increases very sharply between warm working temperatures of 1200°F and 1400°F. A maximum is reached around 1400°F and the strength drop at higher warm working temperatures.

3. Relatively, the increase in surface response is small at the Larson-Miller parameter level of 28.56, i.e., equivalent to 10 hours at 900°F, or to 1.75 hours at 950°F.

Material warm worked at 1200°F exhibited exceptionally low yield strengths. This may be due to the stable, retained austenite that may have formed at the low warm working temperature. The mechanical properties of the specimens which are maraged directly from the warm working temperature of 1400°F compare with those of the solution annealed specimens. Hence, there is no loss in the yield strength if

the 18% nickel alloy (250 Ksi) is maraged directly from the hot-rolled condition.

3.2.3.2 Effect of Warm Work on the Fracture Toughness

The fracture toughness exhibits an approximate drop of 13% when the maraging time at 900°F is changed from 3 to 10 hours for the specimens warm worked at 1400°F. In contrast, it should be noted that the yield strength response of the warm worked material at the two maraging times shows very little change (Figure 51, Table 27).

The longitudinal K_c value for specimens warm worked at 1600°F (900°F/10 hrs) is slightly higher than that of the specimens warm worked at 1400°F. Hence, by interpolation and by taking the tensile data into consideration, it can be deduced that a warm working temperature of 1500°F should give appreciably better properties.

Compared to the fracture toughness of solution annealed specimens, the K_c value of warm worked material is significantly lower. Direct maraging from the hot rolled condition should, therefore, be used only if this simplified treatment offers any distinct advantages in the engineering application under consideration. It should be remembered that the structural and chemical heterogeneities are more pronounced in the "as warm-worked" condition.

3.2.4 Miscellaneous Mechanical Properties

3.2.4.1 Elevated Temperature Properties

Figure 52 and Figure 53 give the mechanical properties of solution annealed and 30% cold worked alloy as a function of testing temperature. The strength properties show a sharp drop at temperatures above 750°F and at 1000°F, the yield strength is about 40-50% the room temperature value.

The effect of solutioning time at 1500°F on the tensile properties is shown in Figure 54. There are no significant effects of the solutioning time and the observed scatter is within the expected experimental error in the tensile properties of sheet specimens when tested at 1000°F.

3.2.4.2 Heat Treat Response of a Thick Section

A 4-1/2" x 4-1/2" x 5-1/4" billet was solution annealed at 1500°F for 1 hour and then aged at 900°F for 3 hours. One hour per inch of thickness was allowed at the respective temperature. Specimens were cut (parallel to the flow lines) at the center and surface of the cube

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in order to compare the tensile properties at the two locations.

The tensile properties at the center and surface of the cube are compared in **Figure** 55 and the results are given in Table 28. The properties at the two locations compare with each other remarkably well and the section size effects are negligible for the billet. The results confirm that the martensite reaction is insensitive to the cooling rate.

3.2.4.3 The Effect of Forging Reduction on Properties

The effect of forging reduction on the properties of the 18% Nickel Alloy (250 KSI) were determined by removing specimens from different locations and directions within the forging. Starting with the conditioned billet, pancake forgings representing 33.8, 50, 66.2, 75 and 84 percent reduction were evaluated. Smooth and notched bar specimens representing the edge and center, in the vertical and horizontal directions defined by the upset, were tested after receiving the following heat treatment:

Solution	1500°F - 1 hr - air cool
Marage	900°F - 10 hrs - air cool

The results of this study are tabulated in Table **29**. Smooth bar tensile data are plotted by the respective position from which specimens were removed in Figures **56 through** 59. Inspection of the plotted data indicates that variation in properties exists between the various locations in the forgings. However, the trend could not be conclusively established because of the small number of specimens tested. Of significant importance is the fact that the billet specimens yielded similar strength and ductility regardless of location or direction. This behavior indicates excellent billet conditioning by the mill supplier. Ultimate strengths ranged from 268 KSI to 278 KSI. Reductions in area ranged from 47 to 60 percent. Considering the mass of the billet studied, these results infer excellent homogenization. In general, the results after upset are uniform in that no great degradation in properties were observed. This is corroborated by inspection of the limited notch tensile and fracture toughness data in Table **29**. The results show that the initial billet data are surprisingly similar to the data exhibited by a pancake forging of 50 percent reduction.

3.2.4.4 Comparison of Sheet and Bar Properties

The sheet and bar stock properties were compared in three solutioning conditions. The tensile properties are compared **in Figure 60** and the results are given in Table **30**. At higher solutioning temperature,

(i.e., @ 1500°F), the strength of the sheet and bar stock are comparable.

3.2.4.5 Fatigue Properties

The smooth and notched fatigue (R.R. Moore rotating beam) properties for the solution annealed material are given in Figure 61. The smooth bar fatigue properties for the 30% cold worked material are given in Figure 62.

The fatigue endurance limits for the various conditions are:

Solution annealed (smooth):	89,000 psi
Solution annealed (notched)	46,000 psi
30% cold worked (smooth):	70,000 psi

3.2.4.6 Impact Properties

Charpy V-notch impact strength of solution annealed and cold worked materials were determined at various testing temperatures. The impact values are plotted as a function of testing temperature for the various conditions in Figures 63 and 64. The Charpy impact values at room temperature for the various conditions of the material are:

Solution Annealed:	55 ft-lbs
30% cold work:	27 ft-lbs
40% cold work:	19 ft-lbs

3.2.4.7 Critical Fracture Toughness Calculations

The critical fracture toughness for the various conditions were calculated using the circumferentially-notched ($K_t > 10$) tensile bars. The results are given in Table 31. As seen from the N.T.S./T.S. ratios, no pertinent conclusions can be drawn from the results since there are no marked differences in the calculated values.

3.2.5 Summary Discussion

The crack propagation resistance in the various conditions are compared in Figure 65 by plotting the K_c values as a function of yield strength in the respective conditions. The data is analyzed by assuming a linear relationship between the two variables and the regression line is approximated by statistical analysis. It is interesting to note that, between the K_c level of 180 Ksi $\sqrt{\text{in.}}$ to 235 Ksi $\sqrt{\text{in.}}$, the cold worked condition is decidedly better because of the substantial improvement in the yield strength. This observation implies that for a design fracture toughness criterion between 180 Ksi $\sqrt{\text{in.}}$ to 230 Ksi $\sqrt{\text{in.}}$ it is better to design a part, whenever

feasible, with small amounts of cold work. The morphology of martensite is altered for small amounts of plastic deformation and the change in morphology can probably account for the excellent fracture characteristics, even at the high strength levels of cold worked material.

It seems from the limited data that, at the same yield strength level, the fracture toughness of warm worked material is lower than the solution annealed condition. As mentioned before, the structural and chemical heterogeneities in warm worked structures can probably account for the differences in fracture morphology of the two conditions.

Examination of fracture surfaces revealed that the alloy generally exhibited an oblique shear mode of fracture in most conditions. There was generally considerable plastic deformation during the initial extension of the crack.

Electron and optical micrographs in the various conditions are shown in **Figures 66** to **Figure 67**. Electron micrographs were taken by the two stage carbon replica techniques. The electron micrographs in **Figure 66** (2 pictures) reveal that the residual effects of working are still apparent when the specimens are solution annealed at 1400°F. The electron micrographs prepared on a solution annealed (1500°F/1 hr) and maraged (900°F/10 hrs) specimens reveals acicular precipitate which may contribute to the hardening of the alloy. The precipitate is not clearly visible in cold worked (40% reduction) specimen which is maraged at 900°F for 1-3/4 hours.

In conclusion, the heat treatments for the various conditions, which give good yield strength and fracture toughness responses, are summarized as follows:

<u>Condition</u>	<u>"Heat Treatment"</u>	
"Solution Annealed"	Solution: Air Cool Marage:	1500°F/1 hr 900°F/10 hrs
"Cold Worked" (30% C.W.)	Direct Marage: from C.W. condition	900°F/2 hrs
"As hot-rolled" (warm working temperature, 1500°F) found optimum by interpolation of results	Direct marage: from hot-rolled condition	900°F/3 hrs

3.2.6 Weld Properties

Hardness, and tensile properties for the 18% nickel alloy (250 KSI) welded in two material conditions are presented in the following sections. In addition, the various filler materials investigated are also compared on the basis of fracture toughness.

3.2.6.1 Hardness Properties

Weld Zone

Vertical hardness traverses taken along the weld centerline for two of the filler wires are listed in Table 32, and are represented graphically in Figure 68. As-welded and aged hardness are compared. The vertical traverses, as shown in Figure 68, represent surveys through both the filler pass (left side) and the fusion pass. Note the comparative uniformity between passes after aging. Little or no difference was observed between the hardness of 250 and 300 KSI filler wire deposits, both of which aged to about 51 Rc. Longitudinal weld hardnesses taken between the weld centerline and the weld-base metal interface showed a similar behavior, Table 33.

Heat-Affected-Zone

Longitudinal hardness surveys in weld-heat-affected zones were taken between the weld-base metal interface and a point in the unaffected base material. Test results are given in Table 34 and are plotted in Figures 69 and 70. The heat-affected zone of the solution heat treated material experienced aging from 35 to 42 Rc in an area approximately 0.250 inches from the weld interface. This effect is clearly defined in the as-welded plot shown in Figure 69. Maraging at 900°F equalized hardness at about 50 Rc in the heat-affected-zone, Figure 69.

A similar behavior was noted in the heat-affected-zone of cold worked material, Figure 70. Aging response was of the same order of magnitude, 41 to 51 Rc, and in approximately the same location as experienced in the solution heat-treated material. Peak hardnesses attained were higher, since they were superimposed on the initial higher hardness (41 Rc) of cold worked material (Figures 69 and 70).

The area of cold worked material adjacent to weld interface, approximately 0.100" wide was completely resolutioned. This was indicated by a loss in hardness from 41 to 33 Rc as shown in the as-welded plot in Figure 69. As anticipated, maraging did not equalize hardness between heat-affected-zone and unaffected base material. The

resolutioned area was lower in hardness, 51 as compared to 55 Rc, Figure 70, but approximately the same as that obtained on solution heat treated material, Figure 69.

The presence of a retained austenite band in the weld heat affected-zone after aging was not definitely established. This area would have been subjected to peak temperatures of 1200-1300°F which are known to promote austenite stabilization. Although not clearly defined in the plotted hardness surveys, a suspected low point was observed after aging in solution heat treated material at a distance of 0.225" from the weld interface, and in the cold worked material at a distance of 0.180" (Table 34). The low points were not excessive and represented a decrease in hardness of about 2 Rc.

3.2.6.2 Tensile Properties

Evaluation of welding filler materials presented in this section are based primarily upon transverse weld tensile tests made with the sheet rolling direction parallel to the test direction. Weld joint efficiencies used for comparison purposes were calculated on the basis of average unwelded sheet tensile properties listed in Table 9. These baseline data are given for each material in each combination of heat treatment and rolling direction evaluated in weld tests.

Solution Heat Treated Base Material (0.140" sheet)

The results of transverse weld tests comparing various filler wire compositions are shown in Table 34 and Figure 71. In preliminary tests made using a maraging treatment of 900°F for 3 hours, the 300 KSI filler wire welds attained 100% yield strength joint efficiency at the 253 KSI level. They exhibited a definite superiority of approximately 20 KSI over the other wires tested, Figure 70. Increasing 900°F maraging time to 10 hours resulted in approximately 100% weld yield strength joint efficiency at about the 265 KSI level in all cases as shown in Figure 70. Maximum average properties (268 KSI) were attained with the high cobalt "cast" filler wire. The matching 250 KSI base material composition welds showed the lowest results (97% yield strength joint efficiency) as based on a 256 KSI yield strength. The excellent performance of the 300 KSI filler wire was further demonstrated by two tensile failures located in parent metal (Table 35).

As previously discussed in section 3.2.1.5 and shown in Figure 42. The maximum yield strength response for the 250 KSI alloy are attained after 10 hours at 900°F. The general improvement in weld properties with increased maraging time is then attributed to the combined effects of increased base material and weld fusion pass hardening response,

as well as improved filler pass hardening response.

Solution Heat Treated Base Material (0.070" sheet)

Transverse weld tensile properties obtained on 0.070" thick sheet, maraged 900°F/10 hours, are presented in Table 36 and Figure 72. **Welds made using the 300 KSI filler wire closely matched base material yield strength (269 KSI), as previously obtained on 0.140" sheet (Table 35), while the two other filler wires evaluated exhibited a reduction in properties to 250 KSI (Figures 71 and 72).**

40% Cold Worked Base Material (0.140" sheet)

Results of transverse tensile tests made on welds produced in cold worked sheet are given in Table 37, and Figure 73. The lower weld yield strengths obtained in these tests, as reflected by decreases of 10 to 15 KSI, are believed to be associated with the shorter 900°F maraging time of 1.75 hours. This treatment is preferred for cold worked material on the basis of studies described in section 3.2.2. The 300 KSI filler material exhibited the highest yield strength properties (256 KSI) of any of the filler wires evaluated. Weld yield strength joint efficiencies were appreciably lower, 88 as compared to 100%, than those reported for welds made in solution heat treated material (Table 35) using the same wires.

Miscellaneous Weld Tensile Properties

Transverse weld tensile tests were made in both solution heat treated and cold worked 0.140" sheet with the rolling direction normal to the direction of test. In these tests only welds produced with the 300 KSI filler wire were evaluated. Test results are given in Table 38. The strength of welds made in solution heat treated sheet and maraged 900°F/10 hours showed no change from the 265 KSI yield strength previously reported in Table 35. Welds made in the cold worked material, however, showed a marked reduction to 231 KSI yield strength with change in rolling direction (Tables 37 and 38). Longitudinal weld tensile test results are presented in Table 39 and Figure 74. Yield strengths ranging from 240 to 249 KSI were obtained in welds made with three different wires and maraged 900°F/3 hours. In case of the 250 KSI and cast-type filler wires, longitudinal weld yield strength was increased over transverse weld yield for the same maraging treatment (Tables 39 and 35). Longitudinal properties of 300 KSI filler welds were equal in ultimate but lower in yield strength than corresponding transverse properties (Tables 39 and 35).

3.2.6.3 Fracture Toughness

Fracture toughness properties of welds made using the various filler materials are given in Table 40. The results are compared graphically on the basis of Kc values in Figure 75. All welded specimens were maraged at 900°F for 10 hours. It should be noted that in preparation, both 300 KSI filler wire specimens were only partially fatigue notched in the weld. The notch was located in the weld filler wire pass and in the heat affected zone in the fusion pass area. The results obtained on these specimens were somewhat higher due to influence of the base material and do not represent a true evaluation of the 300 KSI weld fracture toughness. The fracture toughness of 250 KSI filler wire welds compared favorably with that of the base material on the basis of Kc(KSI $\sqrt{\text{In.}}$) values, 150 (KSI $\sqrt{\text{In.}}$) for weld metal versus 175-216 (KSI $\sqrt{\text{In.}}$) for base material as reported in Table 21. Of the two cast-type filler wires evaluated, the high cobalt, copper-free version (Heat No. 33179) exhibited higher toughness properties. Some measure of the fracture toughness of the 300 KSI filler wire can be obtained by considering test results on welds made using the wire on 300 KSI material shown in Table 66. Welds in this combination of wire and base material exhibited average Kc value of 137 (KSI $\sqrt{\text{In.}}$). The fracture toughness of welds combining 300 KSI filler and 250 KSI sheet should lie somewhere between this value, Kc of 137, and that obtained for the 250 KSI wire and sheet combination (Kc of 150).

3.2.6.4 Summary

The results of welding studies conducted in this investigation revealed that the 18% nickel alloy (250 KSI) possesses a high degree of weldability. This was demonstrated by evaluations based upon the major considerations of weld quality, strength and toughness.

Sound defect-free welds were consistently produced using all filler wires tested by conventional TIG welding procedures without benefit of a "preheat-interpass-postheat" weld thermal cycle. Weld heat-affected-zones in both solution heat treated and cold worked sheet were found to be free of any defects and/or embrittled areas.

A general comparison of filler materials based on weld strength, ductility and toughness as represented by the most significant parameters of yield strength joint efficiency, reduction and Kc respectively are shown in Figure 76. A more detailed evaluation of weld properties is presented in Table 41 where a comparison against base material is also made.

Ductile welds of 100% yield strength joint efficiency can be produced in solution heat treated 250 KSI sheet provided selected filler wires are used, (Figure 76). On the basis of weld test data, the 300 KSI filler wire is preferred, particularly where economic considerations dictate use of a short maraging time of 3 hours (Table 53). Welds made using this wire are equivalent to or higher in strength, and somewhat higher in fracture toughness than welds made with "cast" composition wires, Figure 76. Whenever fracture toughness considerations are paramount, use of the 250 KSI filler wire may be desirable. However, improved fracture toughness is gained only at the sacrifice of yield strength (Figure 76 and Table 59). Cold worked 250 KSI sheet is resolutioned in the weld-heat-affected zone as a result of welding. Transverse weld properties are essentially the same as those of welds in solution heat treated alloy, thus lower weld joint efficiences are experienced in cold worked material (Figure 76). Since, preferred maraging times for cold worked sheet are relatively short to obtain the best balance of strength and toughness, use of the 300 KSI filler wire appears advisable. Test data showed that weld deposits made with this wire responded to aging more rapidly than the others tested, and attained maximum weld joint efficiency (Figure 76).

SHEET SPECIMEN TENSILE TEST

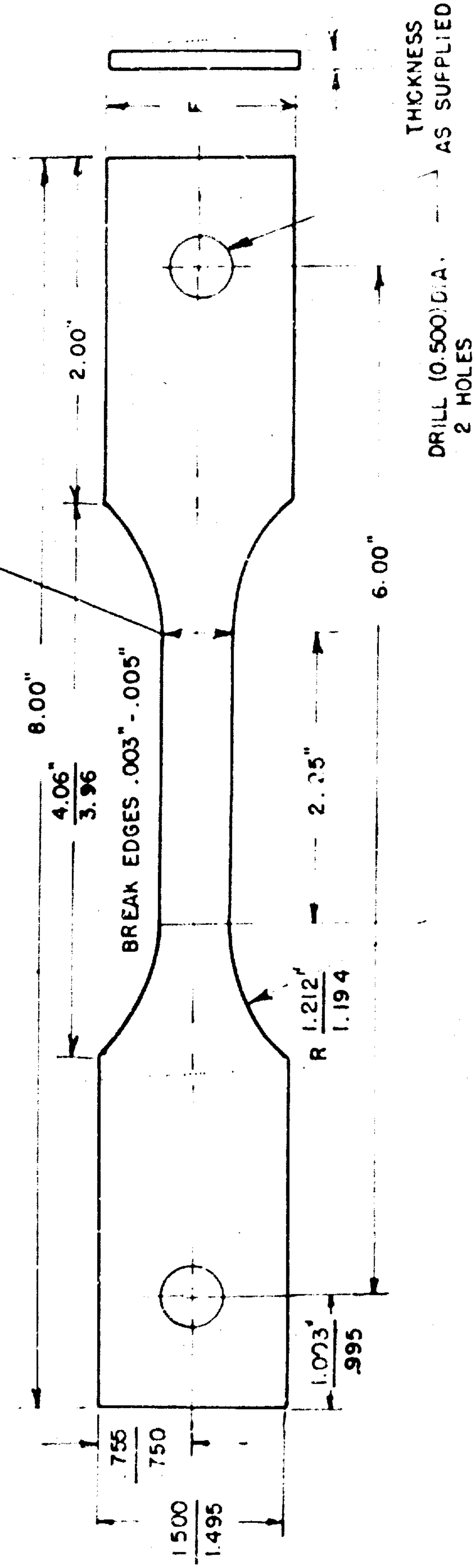
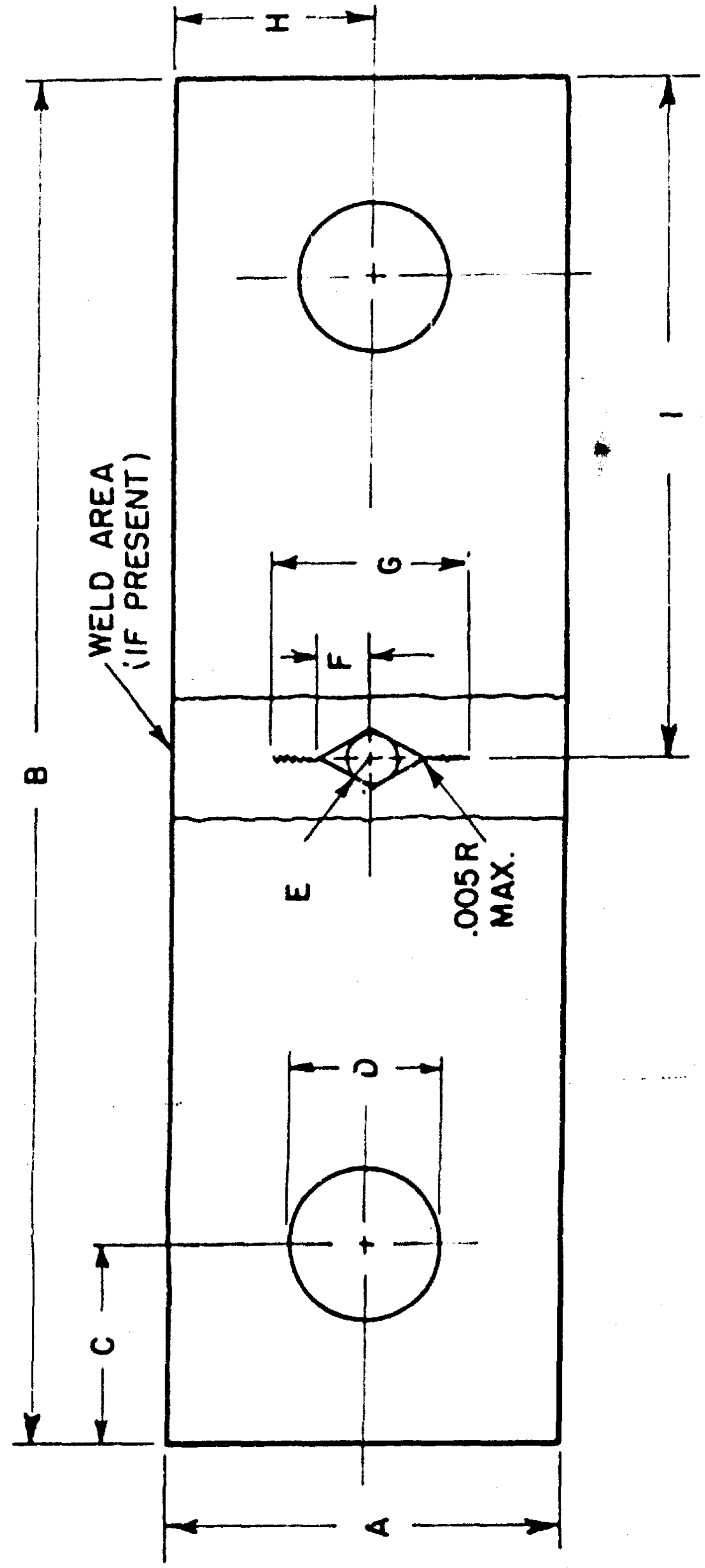


Figure 4

FATIGUE CRACKED SPECIMEN

(CENTER NOTCH)



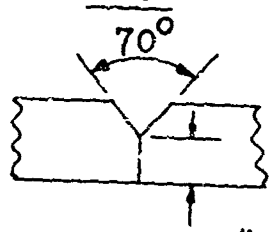
SPECIMEN TYPE	A	B	C	D	E	F	G	H	I
A	2.0	8	1.5 +0.010 -0.000	.75	.25 DIA.	.075 ±0.005	0.8 MAX.	1.0 ±.005	4.0 ±.010

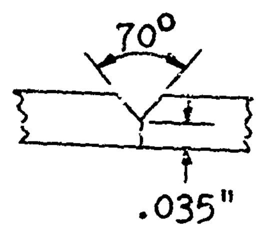
Figure 5

JOINT DESIGN AND WELD SETTINGS FOR
18, 20, AND 25% Ni ALLOYS

THICKNESS: .140" | .070"

JOINT DESIGN

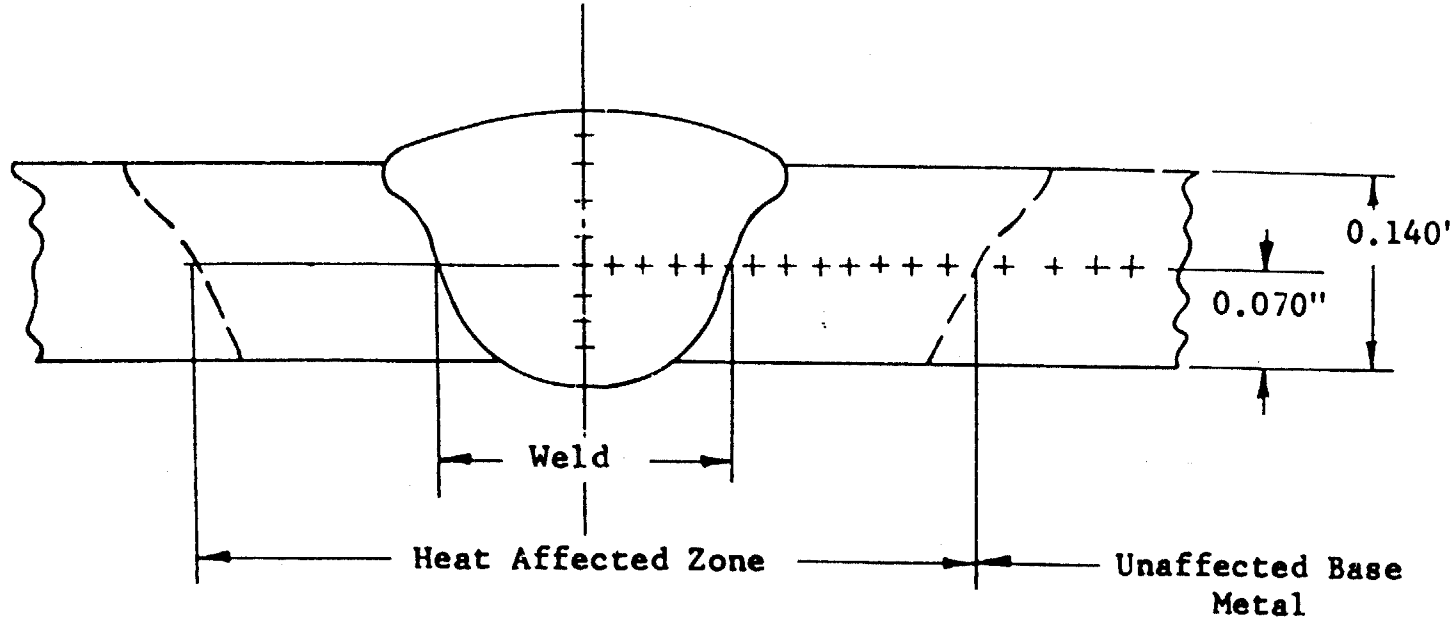




WELD SETTINGS	FUSION PASS	FILLER PASS	FILLER PASS	
Current	120	190	70	Amps
Arc Voltage	10	10.5	15	Volts
Travel Speed	5	5.5	10	in/min
Wire Dia.	-	.062	.062	in
Wire Feed	-	32	32	in/min
Inert Gas	Helium	Argon	Helium	
Nozzle	30	30	30	C.F.H.
Back-Up	4	4	4	C.F.H.
Preheat, Postheat	None	None	None	-
Electrode	5/32" Dia. - 2% Thoriated W			
Back Up Material	Copper			

Figure 6

WEELD ZONE HARDNESS TRAVERSES

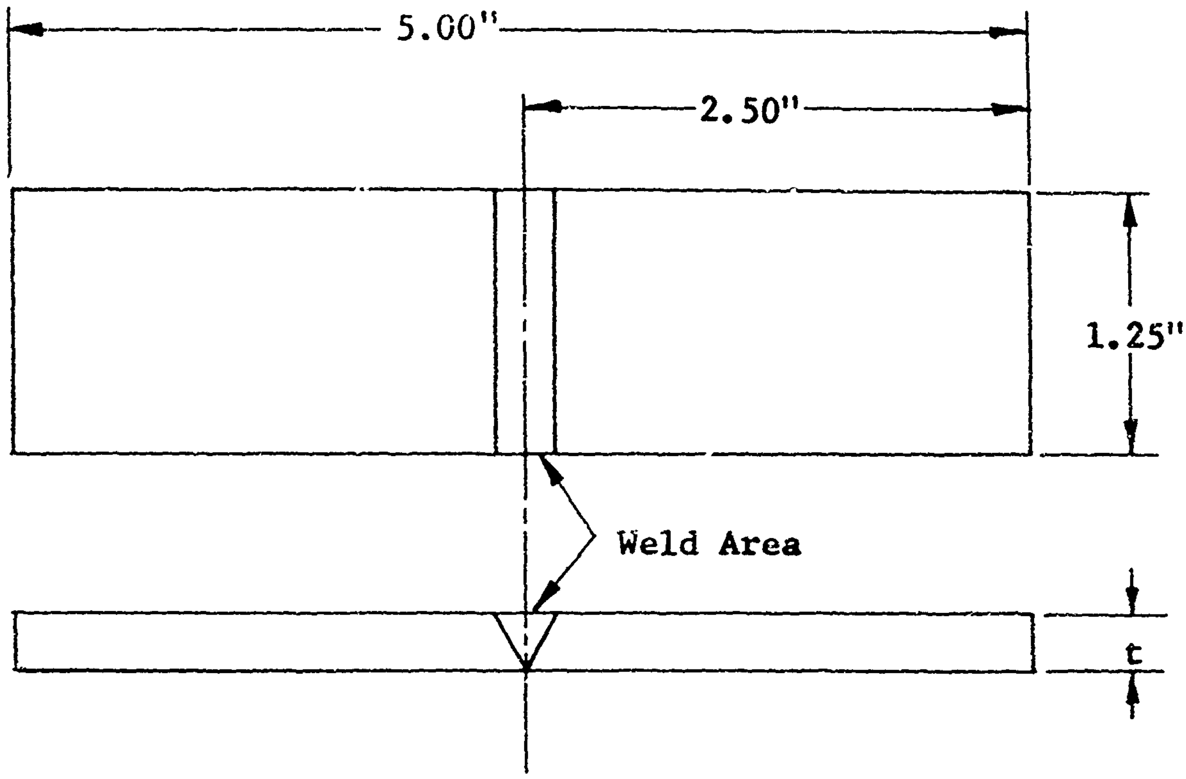


Distance Between Hardness Measurements:

Weld	.020"
HAZ	.015"
B.M.	.025"

Figure 7

WELD BEND TEST SPECIMEN



Note: Weld Area Machined Flush With Parent Sheet (Both Sides)

Figure 8

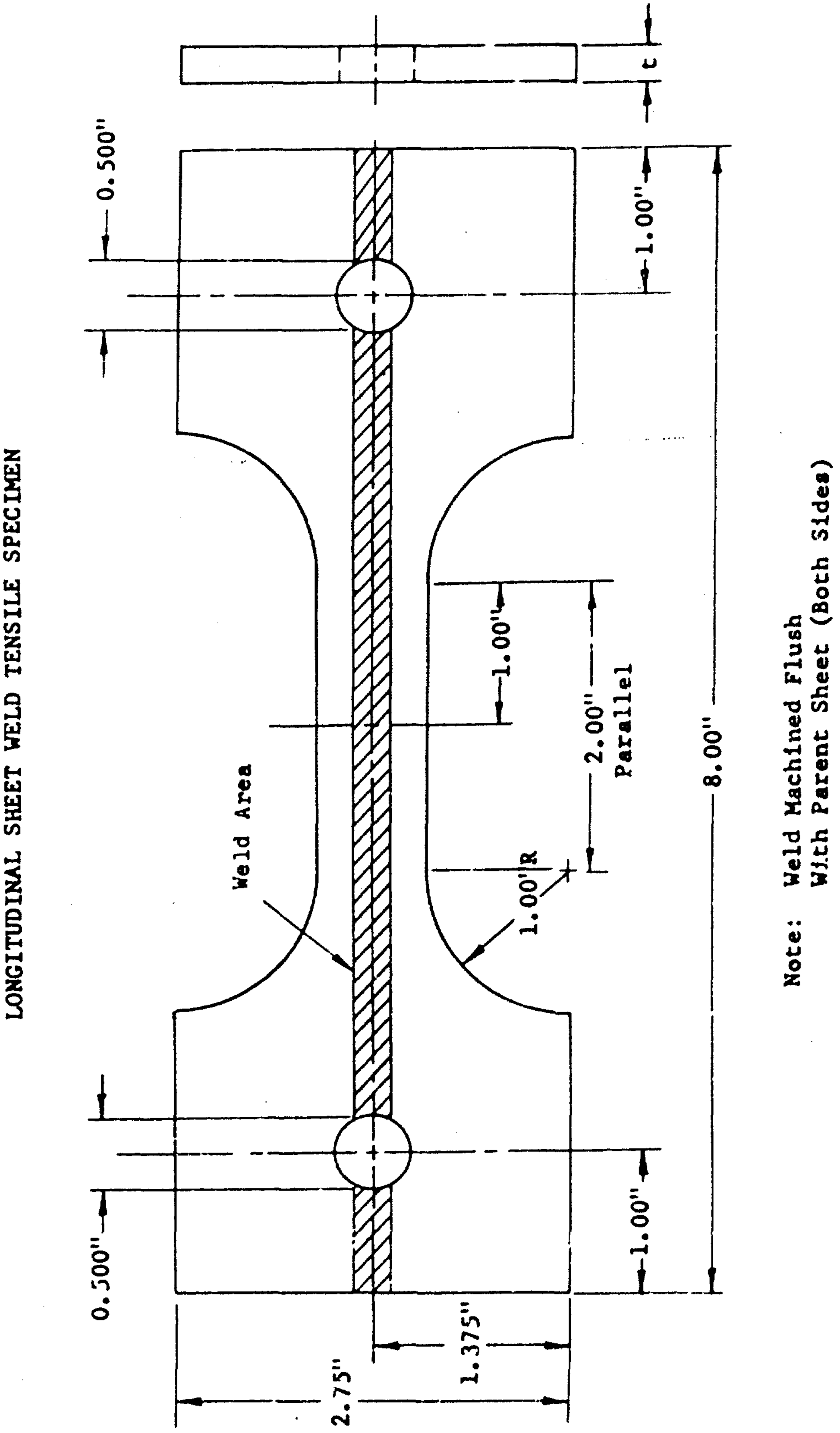
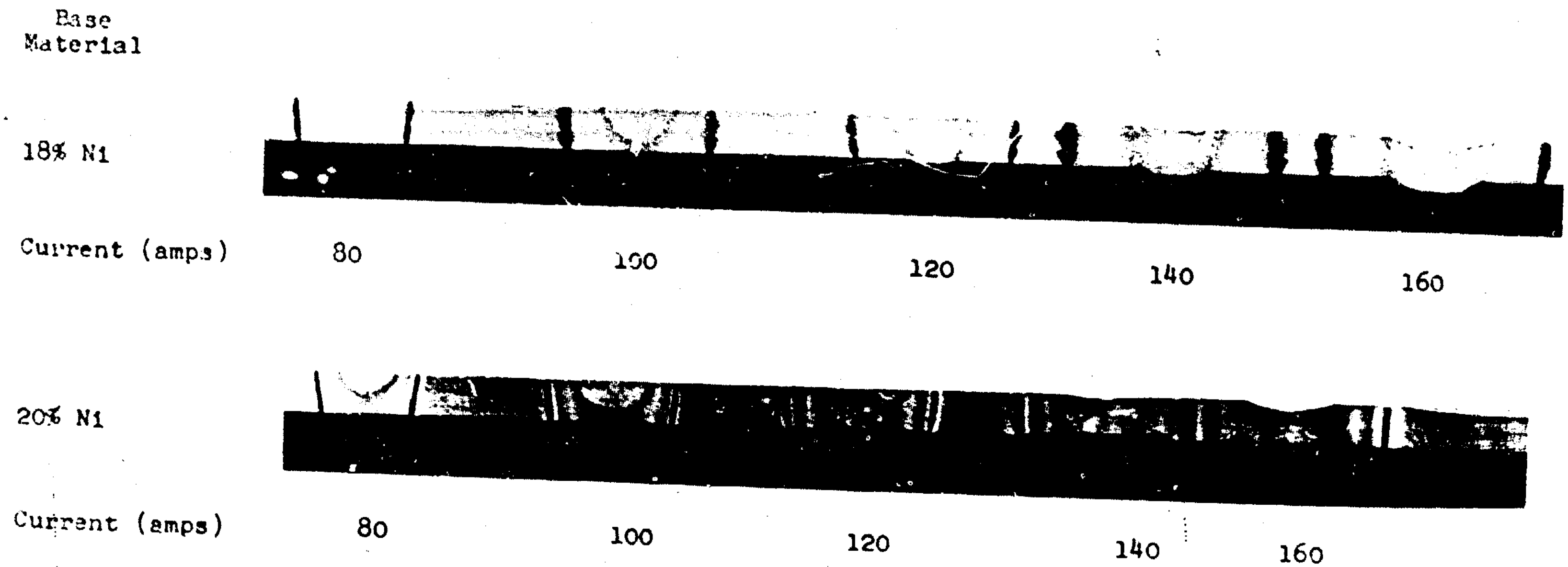

LONGITUDINAL SHEET WELD TENSILE SPECIMEN
0.500"
1.00"
t
1.00"
2.00"
Parallel
8.00"
Weld Area
1.00"R
0.500"
1.00"
1.375"
2.75"
Note: Weld Machined Flush
With Parent Sheet (Both Sides)

Figure 9

EFFECT OF CURRENT ON PENETRATION



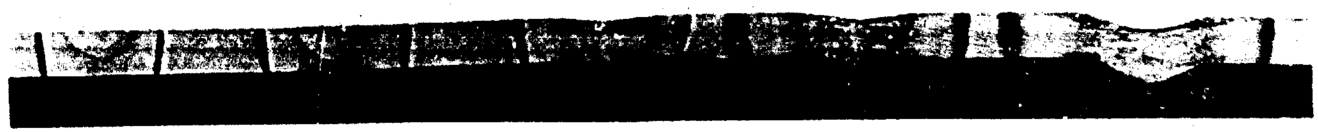
Set Conditions:
Voltage - 10 volts
Travel Speed - 5 ipm
Gas Flow
Nozzle - 30 cfh Argon
Back-Up - 4 cfh Helium
No Filler Added

Figure 10

EFFECT OF VOLTAGE ON PENETRATION

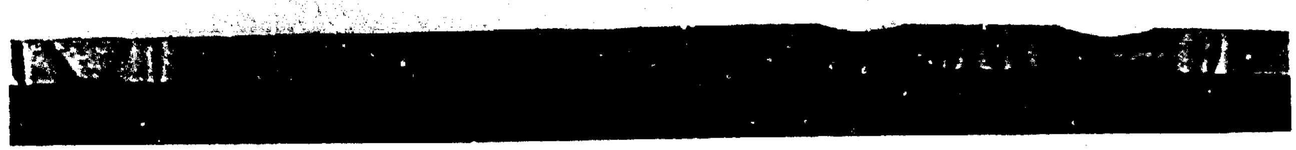
Base Material

18% Ni



Volts 8 10 12 14 16

20% Ni



Volts 8 10 12 14 16

Set Conditions:
Current - 120 amps
Travel Speed - 5 ipm
Gas Flow
Nozzle - 30 cfh Argon
Back-Up - 4 cfh Helium
No Filler Added

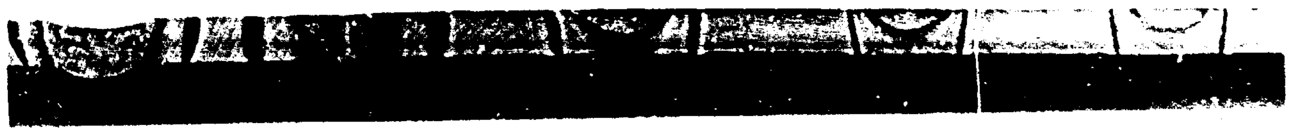
Figure 11

EFFECT OF TRAVEL SPEED ON PENETRATION

(NO FILLER WIRE ADDED)

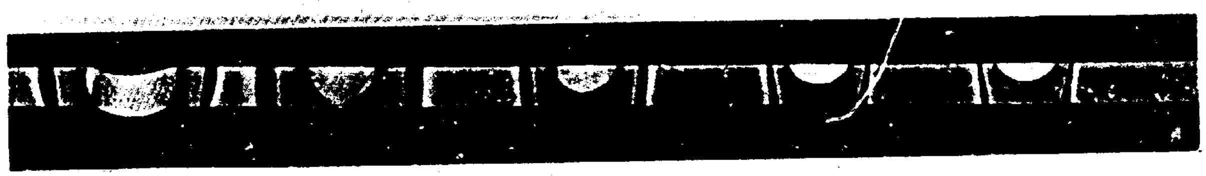
Base Material

18% Ni



Travel Speed (ipm) 3 5 7 9 11

20% Ni



Travel Speed (ipm) 3 5 7 9 11

Set Conditions:
Current - 120 amps
Voltage - 10 volts
Gas Flow
Nozzle - 30 cfh
Back-Up - 4 cfh
No Filler Added

Figure 12

EFFECT OF TRAVEL SPEED ON PENETRATION

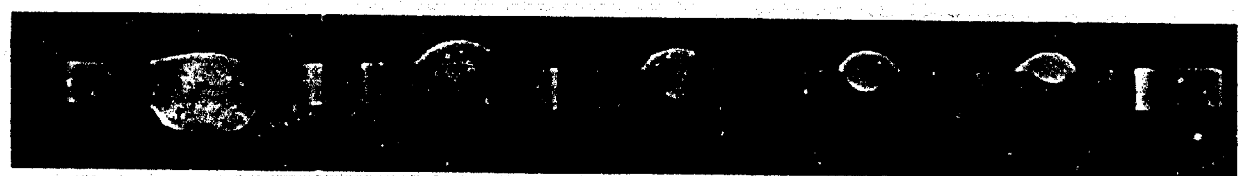
(FILLER WIRE ADDED)

Base Material

18% Ni

Travel Speed (ipm) 3 5 7 9 11

20% Ni



Travel Speed (ipm) 3 5 7 9 11

Set Conditions:
- Current - 120 amps
- Voltage - 10 volts
- Filler Wire Feed Rate - 32 ipm
- Gas Flow
  - Nozzle - 30 cfh Argon
  - Back-Up - 4 cfh Helium

Figure 13

3469

EFFECT OF FILLER WIRE FEED RATE ON PENETRATION

Base Material

18% Ni

Filler Wire Feed (ipm) 24 28 32 36 42

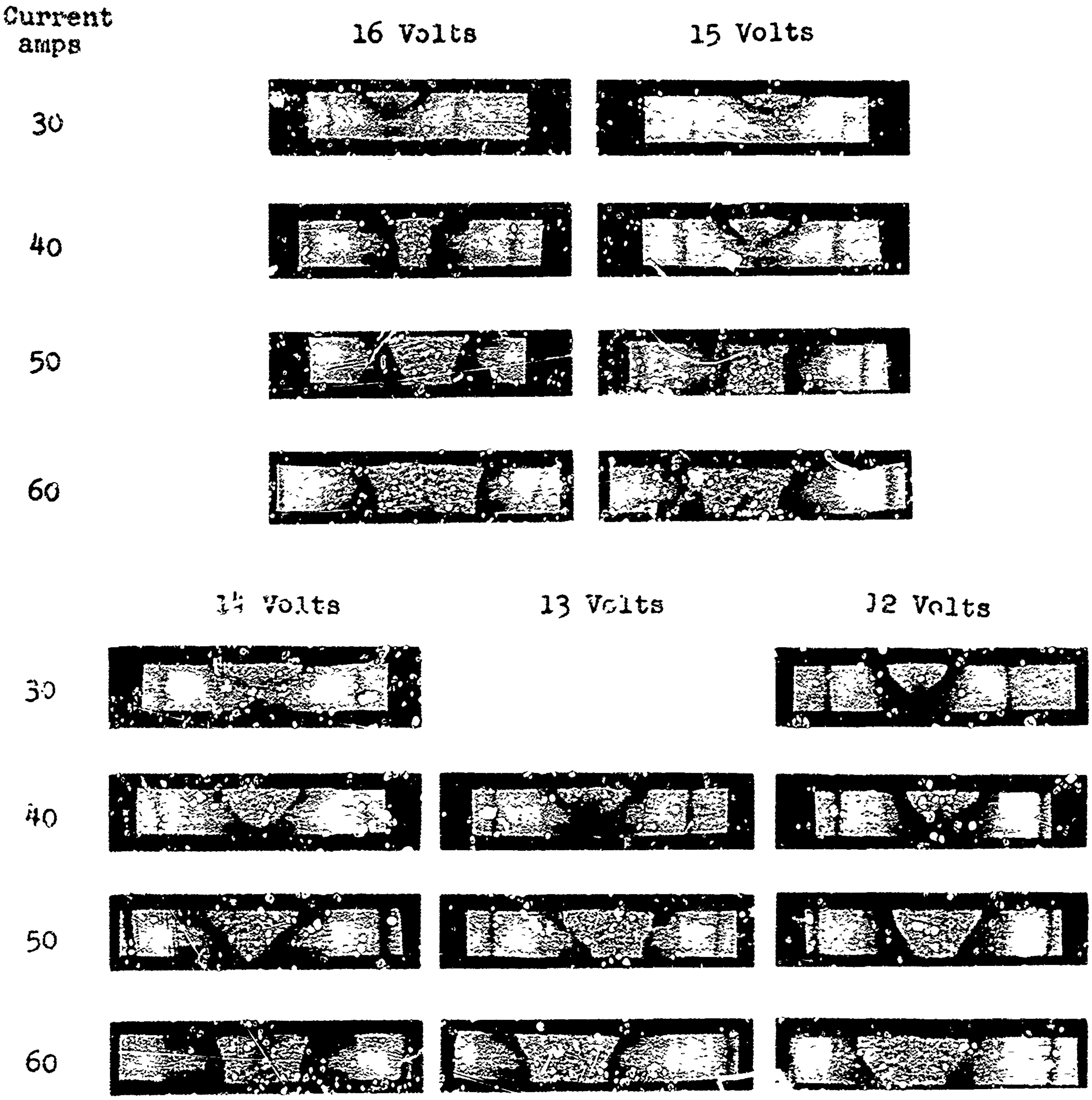
20% Ni

Filler Wire Feed (ipm) 24 28 32 36 42

Set Conditions:
Current - 120 amps
Voltage - 10 volts
Travel Speed - 5 ipm
Gas Flow
Nozzle - 30 cfh Argon
Back-Up - 4 cfh Helium

Figure 14

EFFECT OF VOLTAGE AND AMPERAGE ON PENETRATION
(25% NICKEL ALLOY)



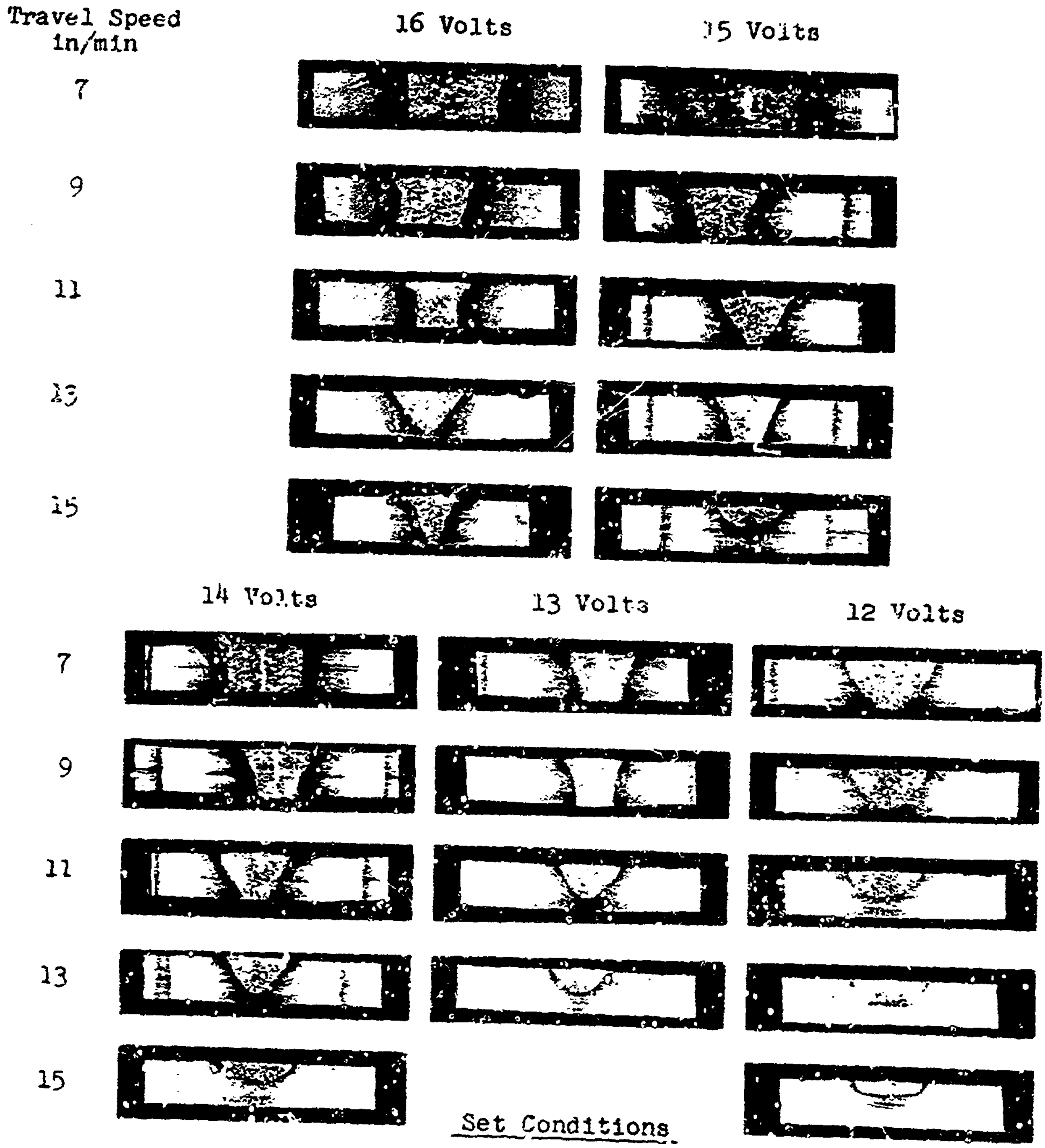
Set Conditions

Travel Speed
10 ipm

Gas Flow
Nozzle - 30 cfh Helium
Back Up - 4 cfh Argon

Figure 15

EFFECT OF TRAVEL SPEED AND VOLTAGE ON PENETRATION
(25% NICKEL ALLOY)



Set Conditions

Current - 50 amps
No Filler Material
Added

Gas Flow
Nozzle - 30 cfh Helium
Back Up - 4 cfh Argon

Figure 16

EFFECT OF FILLER WIRE SPEED ON PENETRATION (25% NICKEL ALLOY)

Wire Feed in/min

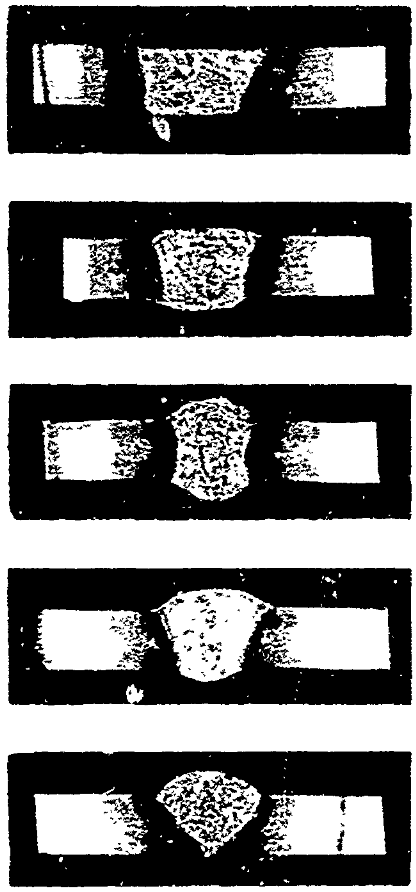
0

7

8

9

10



Set Conditions

Current - 55 amps
Voltage - 16 volts
Travel Speed - 10 ipm

Gas Flow
Nozzle - 30 cfh Helium
Back Up - 4 cfh Argon

Figure 17

TRANSVERSE WELD CROSS SECTION

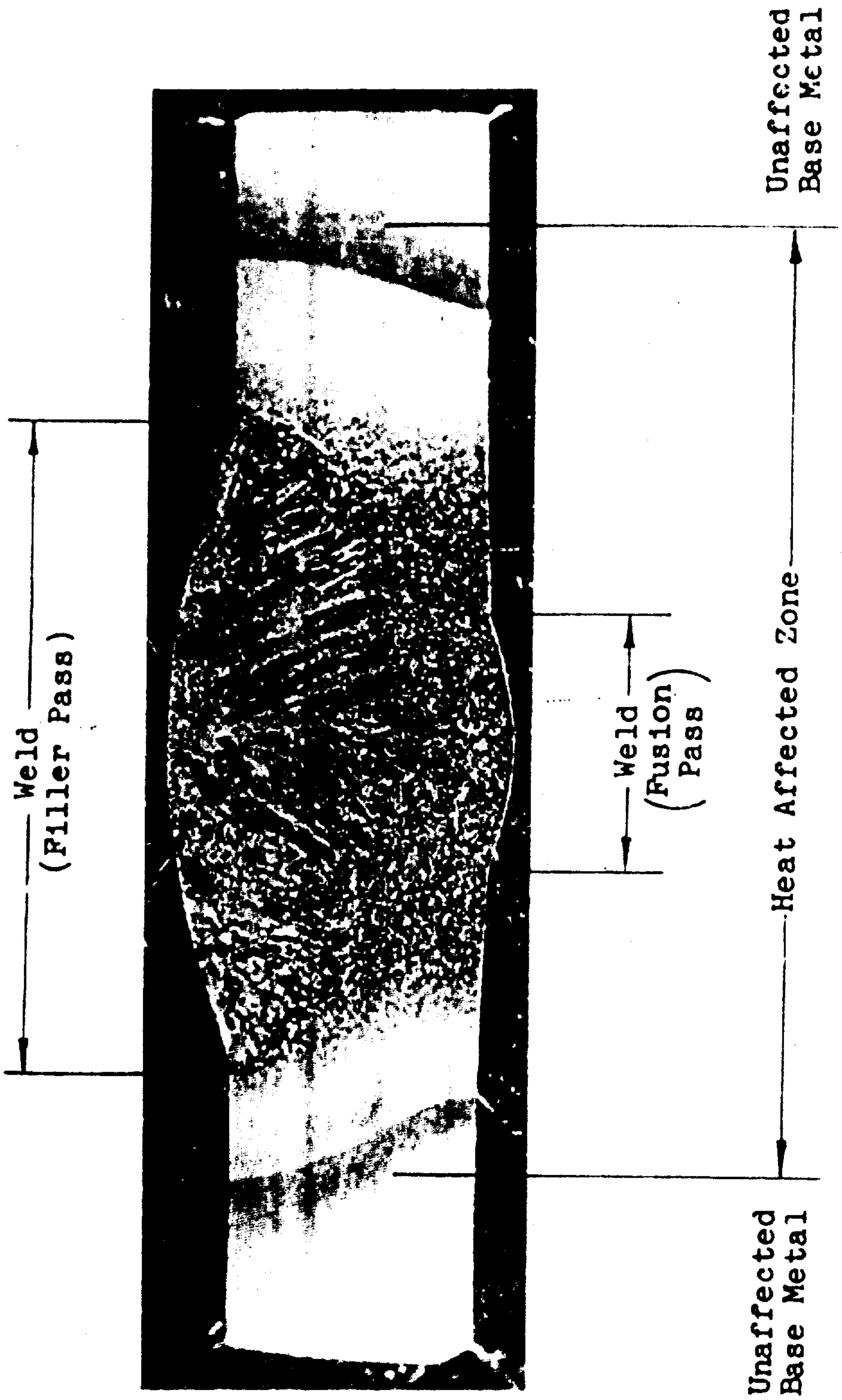


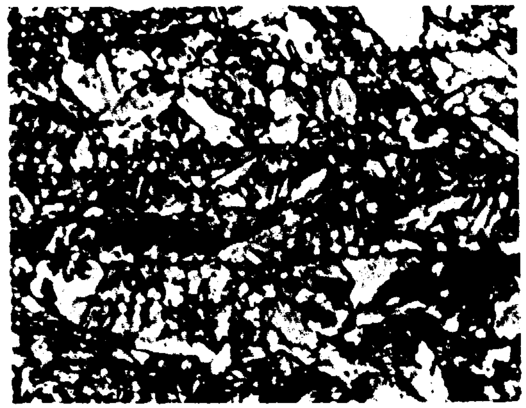
Figure 18

18% NICKEL ALLOY WELDS

Maraged: 900°F/3 Hrs

Filler Pass

300 KSI (7C-054)



Cast (7C-053)

250 KSI (7C-055)

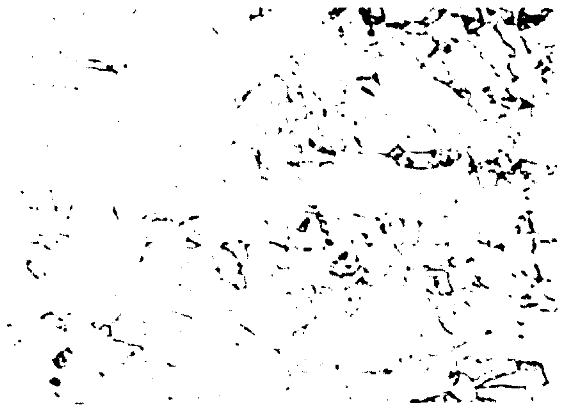
Fusion Pass
(300 KSI)

Figure 19

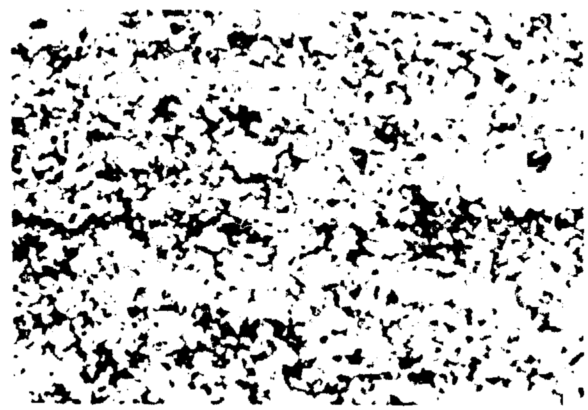
18% NICKEL ALLOY (250 KSI)
SOLUTION HEAT TREATED

Heat Affected Zone

Unaffected Base Metal



As Welded



As Welded

Maraged: 900°F/3 Hrs.

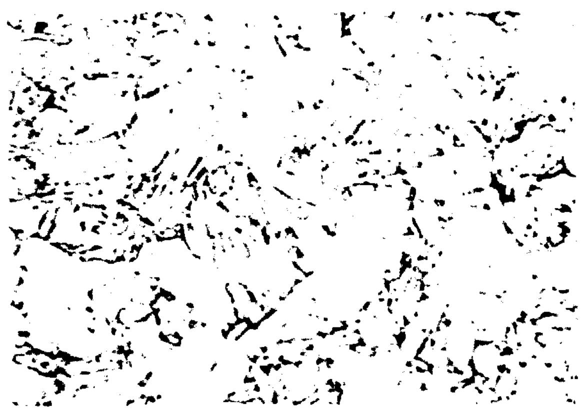
Maraged: 900°F/3 Hrs.

Figure 20

18% NICKEL ALLOY (250 KSI)
40% COLD WORKED

Heat Affected Zone

As Welded



Maraged: 900°F/3 Hrs.

Unaffected Base Metal

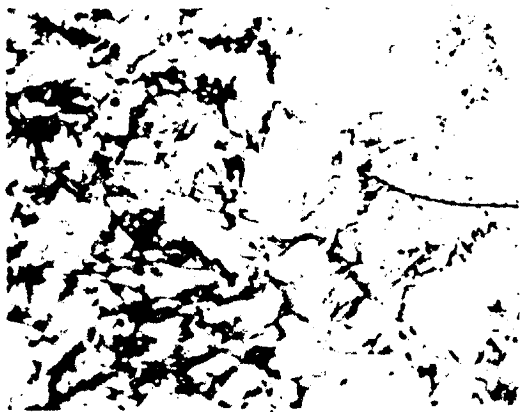
As Welded

Maraged: 900°F/3 Hrs.

Figure 21

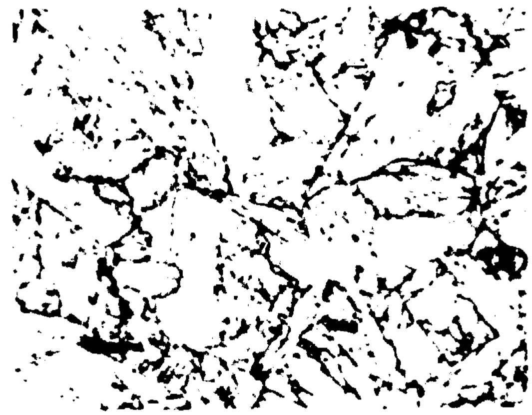
18% NICKEL ALLOY (300 KSI) - SOLUTION HEAT TREATED
WELD HEAT AFFECTED ZONE

Maraged: 900°F/3 Hrs



Weld | Base Metal

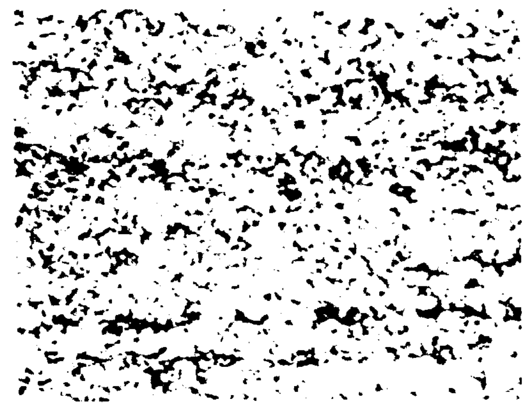
Weld Interface



Heat Affected
Zone 1

Heat Affected
Zone 2

Heat Affected
Zone 3



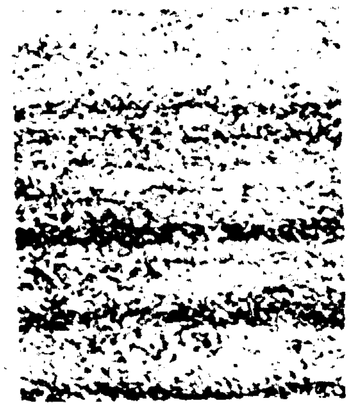
Unaffected
Base Metal

Figure 22

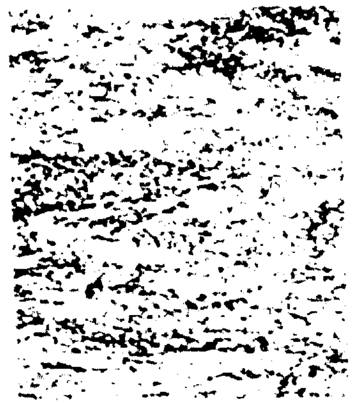
18% NICKEL ALLOY (300 KSI) - 50% COLD WORKED
WELD HEAT AFFECTED ZONE

As Welded

Heat Affected
Zone 1



Heat Affected
Zone 2

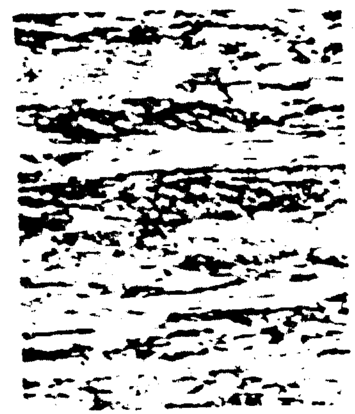


Heat Affected
Zone 3

Unaffected
Base Metal

Aged
900°F/3 Hrs.

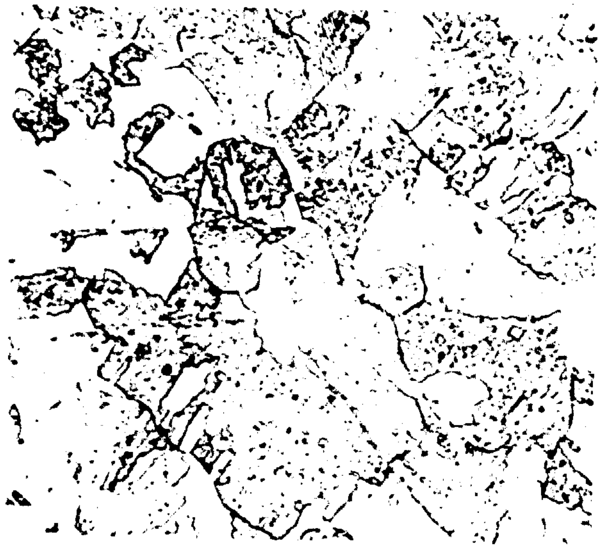
Heat Affected
Zone 1



Unaffected
Base Metal

Figure 23

20% NICKEL ALLOY WELD
(FUSION PASS)



As Welded

Maraged: 850°F/4 Hrs.

Figure 24

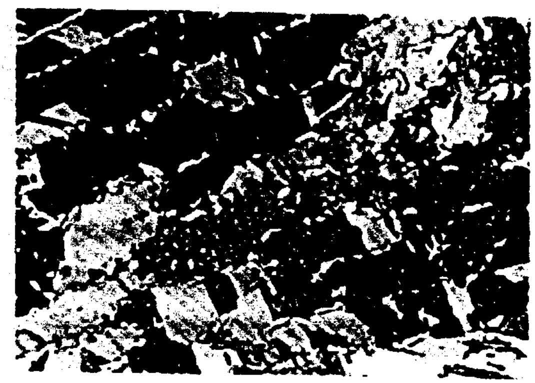
20% NICKEL ALLOY WELDS

Maraged: 850°F/4 Hrs

250 KSI (7C-055)

Mod. 20% Ni (7C-058)

Mod. 20% Ni+Mo (7C-059)



20% Ni+Mo (7C-060)

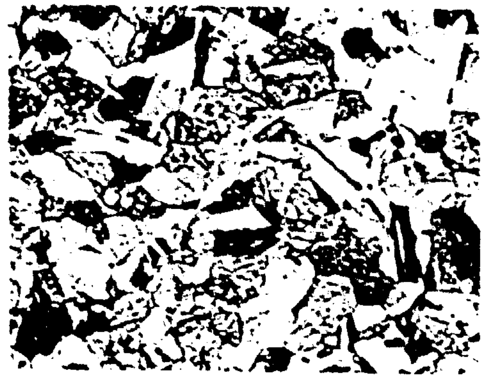
Figure 25

20% NICKEL ALLOY - SOLUTION HEAT TREATED
WELD HEAT AFFECTED ZONE

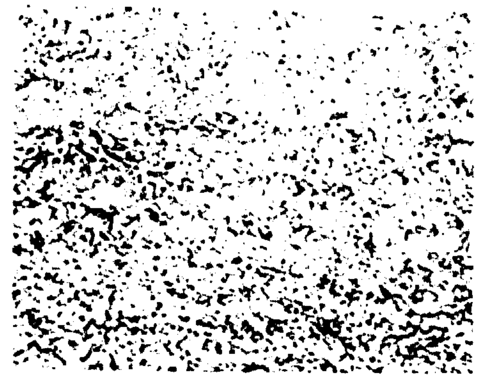
Maraged: 850°F/4 Hrs

Weld | Base Metal

Weld Interface

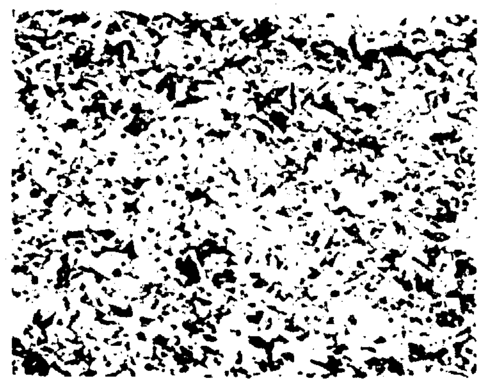


Heat Affected Zone 1



Heat Affected Zone 2

Heat Affected Zone 3



Unaffected Base Metal

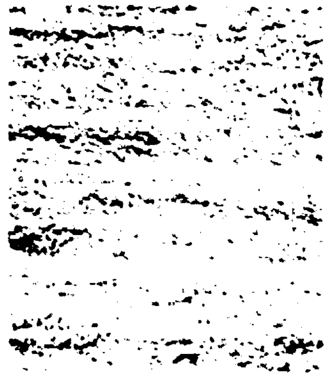
Figure 26

3857

20% NICKEL ALLOY - 50% COLD WORKED
WELD HEAT AFFECTED ZONE

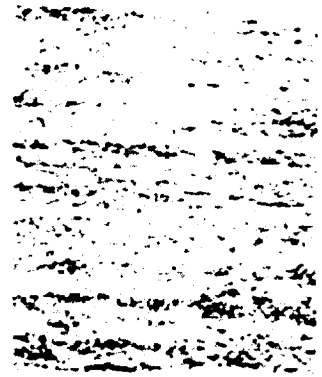
As Welded

Heat Affected
Zone 1



Heat Affected
Zone 2

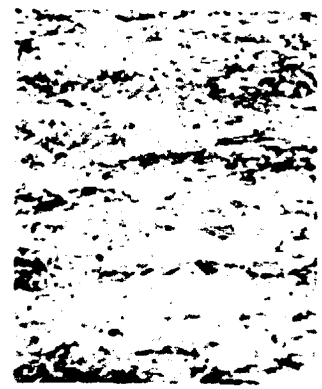
Heat Affected
Zone 3



Unaffected
Base Metal

Aged
850°F/4 Hrs.

Heat Affected
Zone 1



Unaffected
Base Metal

Figure 27

3852

25% NICKEL ALLOY WELD
(FUSION PASS)

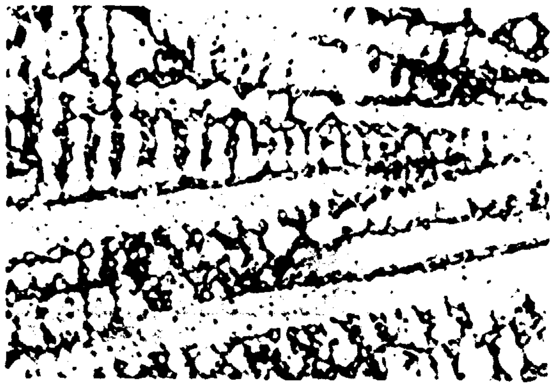
As Welded

Ausaged: 1300°F/4 Hrs. + Ref, -110°F/16 Hrs.
Maraged: 850°F/4 Hrs.

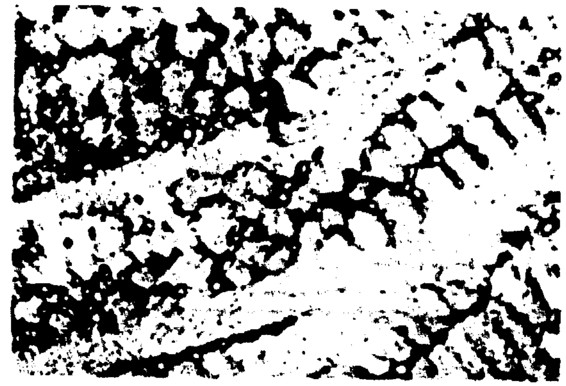
Figure 28

25% NICKEL ALLOY WELDS

Aged: 1300°F/4 Hrs + Ref. -110°F/16 Hrs + 850°F/4 Hrs

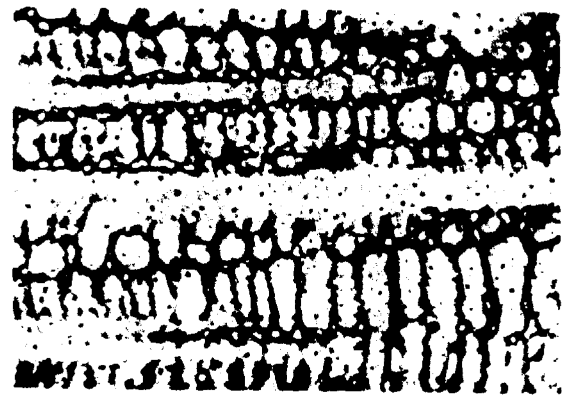


250 KSI (7C-055)



Mod. 20% Ni (7C-058)

Mod. 20% Ni+Mo (7C-059)



20% Ni+Mo (7C-060)

Figure 29

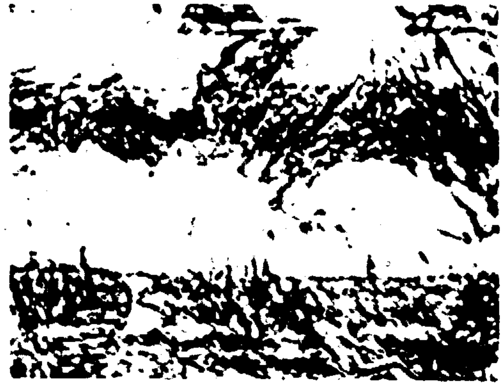
3853

25% NICKEL ALLOY - SOLUTION HEAT TREATED
WELD HEAT AFFECTED ZONE

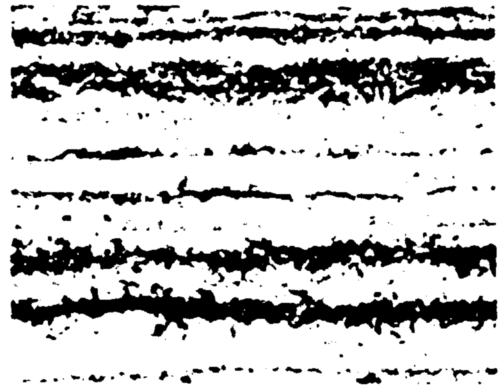
Aged: 1300°F/4 Hrs + Ref. -110°F/16 Hrs + 850°F/4 Hrs

Weld | Base Metal

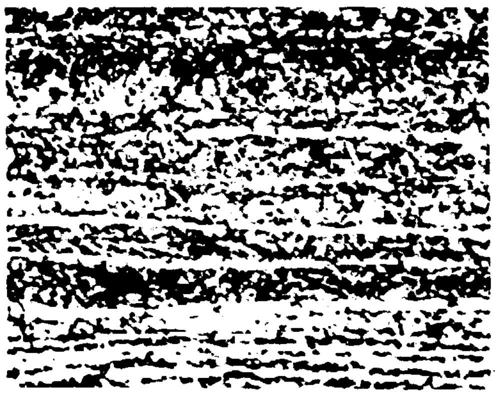
Weld Interface



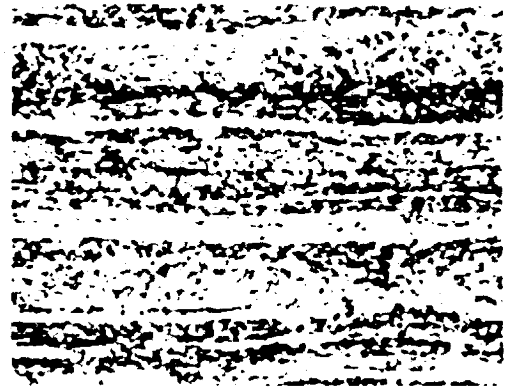
Heat Affected
Zone 1



Heat Affected
Zone 2



Heat Affected
Zone 3



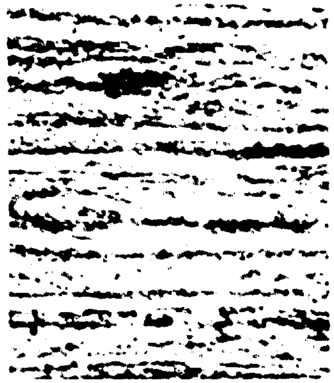
Unaffected
Base Metal

Figure 30

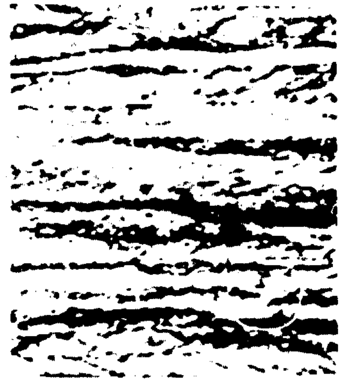
25% NICKEL ALLOY - 30% COLD WORKED
WELD HEAT AFFECTED ZONE

As Welded

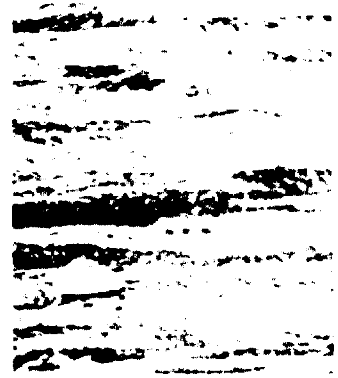
Heat Affected
Zone 1



Heat Affected
Zone 2



Heat Affected
Zone 3



Unaffected
Base Metal

Aged

1300°F/4 Hrs.
-110°F/16 Hrs.
850°F/4 Hrs.

Heat Affected
Zone 1

Unaffected
Base Metal

Figure 31

TABLE 1

CHEMICAL COMPOSITION OF ALLOYS EVALUATED
UNDER CONTRACT AF 33 (616) - 8018

ELEMENT	18% NICKEL ALLOY (250 KSI) HEAT NO. 23832	18% NICKEL ALLOY (300 KSI) HEAT NO. 23831	20% NICKEL ALLOY HEAT NO. 23826	25% NICKEL ALLOY HEAT NO. 23825
Carbon	0.010	0.008	0.007	0.006
Manganese	0.014	0.015	0.035	0.035
Phosphorus	0.003	0.001	0.001	0.001
Sulphur	0.002	0.003	0.003	0.002
Silicon	0.04	0.05	0.04	0.06
Nickel	18.60	18.61	20.19	25.75
Molybdenum	5.04	5.00	-	1.42
Titanium	0.42	0.71	1.56	-
Aluminum	0.08	0.13	0.30	0.31
Cobalt	7.74	9.05	-	-
Zirconium	0.003	0.005	0.006	0.007
Calcium	0.001	0.001	-	0.001
Columbium	-	-	0.44	0.467
Boron	0.002	0.002	0.005	0.003

TABLE 2

COMPOSITION SPECIFICATIONS AND CHEMICAL ANALYSES OF HEATS FOR DETERMINING PROPERTY VARIATIONS FROM UPPER TO LOWER LIMITS OF COMPOSITION SPECIFICATION OF THE 300 KSI NOMINAL YIELD STRENGTH 18% NICKEL ALLOY

	Heat #7C056		Heat #7C057	
Element	Spec.	Analysis	Spec.	Analysis
Carbon	0.01/0.03	0.026	0.01/0.03	0.023
Manganese	0.10 max	0.002	0.10 max	0.002
Phosphorus	0.010 max	0.008	0.010 max	0.006
Sulphur	0.010 max	0.006	0.010 max	0.007
Silicon	0.10 max	0.01	0.10 max	0.01
Nickel	18.0/19.0	18.13	18.0/19.0	18.28
Molybdenum	4.62/4.78	4.67	5.12/5.28	5.17
Titanium	0.42/0.58	0.50	0.72/0.88	0.81
Aluminum	0.10 added	0.12	0.10 added	0.071
Cobalt	8.40/8.60	8.57	9.40/9.60	9.40
Boron	0.003 added	NA	0.003 added	NA
Zirconium	0.02 added	NA	0.02 added	NA
Calcium	0.05 added	NA	0.05 added	NA

NA = Not Analyzed

TABLE 3

PROCESSING OF HIGH AND LOW CHEMICAL COMPOSITION HEATS OF 18% NICKEL (300 KSI) ALLOY

1. Heat Size - 60#

2. Melting Method - Vacuum Induction - vacuum arc remelt

3. Yield - 60# Low chemistry, designated 7C056
   60# High chemistry, designated 7C057

4. Mill Products - 30# in form of 3/4" bar stock
   hot rolled from 1800°F, finish at 1500°F.
   30# in form of 0.115" sheet
   30% and 50% cold rolled sheets finished from start gages of 0.164" and 0.230", respectively.

5. Specimens Removed -
   a. Rd bar tensile, 0.252"Dx1" gage length
   b. Rd bar sharp notch tensile, notch radius less than 0.001" ($K_t = 12$).
   c. Edge notch G_c specimen (ASTM Type)

TABLE 4

PRELIMINARY MECHANICAL PROPERTIES DATA ON 60 POUND LOW CHEMISTRY
300 KSI NOMINAL YIELD STRENGTH 18% NICKEL ALLOY
HEAT NO. 7C056

Heat Treatment and Cold Work	UTS KSI	.2% YS KSI	Elong. %	R.A. %	**N.T.S KSI	***N.F.S. KSI	*K_c KSI/in	*G_c In.Lb/In^2
Sheet								
3 hrs/900°F	272	264	6.0	39.0	217	231	204	1280
3 hrs/900°F					198.5	218.5	187	1250
15 min/1500°F+ 3 hrs/900°F	268	266	5.5	37.	209	229	230	1835
15 min/1500°F+ 3 hrs/900°F	264	258	6.0	38.				
30% CW + 3 hrs/900°F	291	287	7.5	38	215	244.5	198	1310
30% CW + 3 hrs/900°F	292	289	5	33				
50% CW + 3 hrs/900°F	303	-	5	34	167.5	187	150	800
50% CW + 3 hrs/900°F	303	302	4	35	166.5	196	190	1250

Bar	UTS KSI	.2% YS KSI	Elong.- 4D %	R.A. %	****N.T.S.	N.T.S. / U.T.S.
30 min/1500°F+3 hrs/900°F	273	265	19	59	415	1.50
30 min/1500°F+3 hrs/900°F	275	271	12	61	411	
30 min/1500°F+3 hrs/900°F	276	273	11	63	404	
3 hrs/900°F	263	261	10	53	407	1.53
3 hrs/900°F	271	268	10	62	414	
3 hrs/900°F	273	270	11	61	410	

* 2" W x .115" B ASTM edge notch specimen values.

** Notch Tensile Ultimate - $P/(W-2a_o)$ (B)

*** NFS - Net Fracture Strength - $P/(w-2a)$ (B)

**** 0.300 Major Diameter, K_t = 12

TABLE 5

PRELIMINARY MECHANICAL PROPERTIES DATA ON 60 POUND HIGH CHEMISTRY 300 KSI NOMINAL YIELD STRENGTH 18% NICKEL ALLOY HEAT NO. 7C057

Heat Treatment and Cold Work	UTS KSI	.2% Y.S. KSI	Elong. %	R.A. %	NS KSI	NFS KSI	K_c KSI $\sqrt{In}$	G_c In Lb/In^2
Sheet								
3 hrs/900°F	314	306	5.0	34	157	175	140	700
3 hrs/900°F	311	305	5.0	25	161.5	194	155	900
15 min/1500°F+3 hr/900°F	314	308	5.0	28	138	148.5	119	500
15 min/1500°F+3 hr/900°F	314	309	5.0	29				
30% CW + 3 hr/900°F	335	333	-	45	131	186.5	135	625
30% CW + 3 hr/900°F	329	323	5	47	132	197	140	700
50% CW + 3 hr/900°F	339	337	4	41	113.5	136	104	400
50% CW + 3 hr/900°F	340	338	4	38	132.8	159.5	130	600

Bar	UTS KSI	.2% Y.S. KSI	Elong. 4D %	R.A. %	N.T.S. KSI	N.T.S./U.T.S.
30 min/1500°F+3 hr/900°F	321	316	11	57	405	1.26
30 min/1500°F+3 hr/900°F	317	312	11	56	385	
30 min/1500°F+3 hr/900°F	317	313	11	56	412	
3 hrs/900°F	316	311	10	57	429	1.37
3 hrs/900°F	317	314	10	56	448	
3 hrs/900°F	318	314	11	55	426	

TABLE 6

COMPOSITION SPECIFICATIONS AND CHEMICAL ANALYSES OF WELD WIRE HEATS

	Cast-250 KSI Heat 7C-053		250 KSI Heat 7C-055		300 KSI Heat 7C-054	
Element	Spec	Analysis	Spec	Analysis	Spec	Analysis
Carbon	0.01/0.03	0.028	Same	0.023	Same	0.026
Manganese	0.10 max.	0.003	Same	0.002	Same	0.002
Phosphorus	0.010 max.	0.008	Same	0.007	Same	0.006
Sulphur	0.010 max.	0.007	Same	0.006	Same	0.006
Silicon	0.10 max.	0.014	Same	0.014	Same	0.014
Nickel	15.5/16.5	15.99	18.0/19.0	18.61	18.0/19.0	18.13
Molybdenum	4.7/5.1	4.92	4.7/5.1	5.02	4.7/5.1	4.07
Titanium	0.30/0.50	0.40	0.40/0.60	0.54	.60/.80	0.72
Aluminum	0.10 added	0.15	0.10 added	0.14	0.10 added	0.089
Columbium	--	--	--	--	--	--
Cobalt	9.5/10.5	10.28	7.0/8.0	7.66	8.5/9.5	8.96
Copper	1.0/2.0	1.54	--	--	--	--
Boron	0.003 added	N.A.	Same	N.A.	Same	N.A.
Zirconium	0.02 added	N.A.	Same	N.A.	Same	N.A.
Calcium	0.05 added	N.A.	Same	N.A.	Same	N.A.

N.A. = Not Analyzed

Table 7

COMPOSITION OF WELD WIRE HEAT NO. 33179 (1)

Element	Nominal Analysis
Nickel	17
Cobalt	11
Molybdenum	4.6
Titanium	0.4
Aluminum	0.1

(1) International Nickel Co., Inc. experimental air-melted "Cast" composition, 0.003 boron, 0.02 zirconium, and 0.05 calcium added.

TABLE 8

COMPOSITION SPECIFICATIONS AND CHEMICAL ANALYSES OF WELD WIRE HEATS

	20% $N_i + M_o$ Heat 7C-060		Mod. 20% N_i Heat 7C-058		Mod. 20% $N_i + M_o$ Heat 7C-059	
Element	Spec	Analysis	Spec	Analysis	Spec	Analysis
Carbon	0.01/0.03	0.018	Same	0.023	Same	0.024
Manganese	0.10 max.	0.002	Same	0.002	Same	0.002
Phosphorus	0.010 max.	0.004	Same	0.006	Same	0.006
Sulphur	0.010 max.	0.009	Same	0.006	Same	0.006
Silicon	0.10 max.	0.033	Same	0.088	Same	0.0094
Nickel	19.5/20.5	19.73	17.5/18.5	17.74	17.5/18.5	17.51
Molybdenum	1.40/1.60	1.45	--	--	1.40/1.60	1.465
Titanium	1.60/1.80	1.78	1.60/1.80	1.78	1.60/1.80	1.74
Aluminum	0.15/0.30	0.21	0.15/0.30	0.18	0.15/0.30	0.15
Columbium	0.30/0.50	0.50	0.30/0.50	0.48	0.30/0.50	0.51
Cobalt	--	--	--	--	--	--
Copper	--	--	--	--	--	--
Boron	0.003 added	N.A.	Same	N.A.	Same	N.A.
Zirconium	0.02 added	N.A.	Same	N.A.	Same	N.A.
Calcium	0.05 added	N.A.	Same	N.A.	Same	N.A.

N.A. = Not Analyzed

Table 9

SHEET TENSILE PROPERTIES
BASIS FOR CALCULATION OF WELD JOINT EFFICIENCIES

Alloy	Condition(1)	Ausage Temp °F	Ausage Time Hours	Marage Temp °F	Marage Time Hours	Orientation of Specimen Axis to Rolling Direction	UTS KSI	0.2% YS KSI
300 KSI	SHT			900	3	Parallel	293	284
	50% CW			900	3		338(2)	337(2)
				900	5.5		342(2)	341(2)
250 KSI	SHT			900	3	Parallel	266	253
	SHT			900	10		275	264
	40% CW			900	3		297	294
				900	1.75		295	292
25% Ni(3)	SHT	1300	4	850	4	Parallel	273	262
	SHT(4)	1200	4	900	3		288	267
	30% CW			900	1		266	230
20% Ni	SHT			850	4	Parallel	269	264
	SHT(4)			900	10		255	250
	50% CW			900	10		295	293
300 KSI	SHT			900	3	Normal	298(2)	295(2)
	50% CW			900	3		361(2)	358(2)
	50% CW			900	5.5		325(2)	320(2)
250 KSI	SHT			900	3	Normal	264(2)	262(2)
	SHT			900	10		281	271
	40% CW			900	3		320	316
	40% CW			900	1.75		309	306

(1) SHT - Solution Heat Treated, 1500°F/1 hr. Air Cool

(2) No data points, figures represent estimates based on best available data

(3) 25% Nickel Alloy refrigerated after ausaging: 16 hours at - 110°F

(4) Solution Heat Treated: 1450/1 hr., Air Cool

Table 10

TRANSVERSE WELD BEND TEST DATA
18% Ni STEEL (250 KSI) (1) (2)

Filler Wire		Material	Minimum
Type	Heat No.	Thickness-in	Bend Radius-T
250 KSI	7C-055	0.140	2
300 KSI	7C-054	0.140	1
Cast	7C-053	0.140	3
250 KSI	7C-055	0.70	2
300 KSI	7C-054	0.70	1
Cast	7C-053	0.70	1

(1) Base material solution heat treated

(2) All tests represent face bends on as-welded specimens

7c

Table 11

TRANSVERSE WELD BEND TEST DATA
18% Ni STEEL (300 KSI) (1) (2)

Filler Wire		Material	Minimum
Type	Heat No.	Thickness-in	Bend Radius-T
300 KSI	7C-054	0.140	3
Cast	7C-053	0.140	3
Cast	33179	0.140	2
300 KSI	7C-054	0.070	2
Cast	7C-053	0.070	1

(1) Base material solution heat treated

(2) All tests represent face bends on as-welded specimens

TABLE 12

TRANSVERSE WELD BEND TEST DATA
20% Ni STEEL (1) (2)

Filler Wire Type	Heat No.	Material Thickness-in	Minimum Bend Radius-T
300 KSI	7C-054	0.140	3
Mod. 20% Ni	7C-058	0.140	>3
Mod. 20% Ni + Mo	7C-059	0.140	3
20% Ni + Mo	7C-060	0.140	>3
300 KSI	7C-054	0.070	2
Mod. 20% Ni + Mo	7C-059	0.070	2
20% Ni + Mo	7C-060	0.070	1

(1) Base material solution heat treated

(2) All tests represent face bends on as-welded specimens

Table 13

TRANSVERSE WELD BEND TEST DATA
25% Ni STEEL (1) (2)

Filler Wire Type	Heat No.	Material Thickness	Minimum Bend Radius-T
300 KSI	7C-054	0.140	2
250 KSI	7C-055	0.140	1
Mod. 20% Ni	7C-058	0.140	2
Mod. 20% Ni + Mo	7C-059	0.140	1
20% Ni + Mo	7C-060	0.140	2
300 KSI	7C-054	.070	2
Mod. 20% Ni + Mo	7C-059	.070	2

(1) Base material solution heat treated

(2) All tests represent face bends on as-welded specimens

HARDNESS RESPONSE CONTOURS OF SOLUTION ANNEALED
18% NICKEL ALLOY (250 KSI)

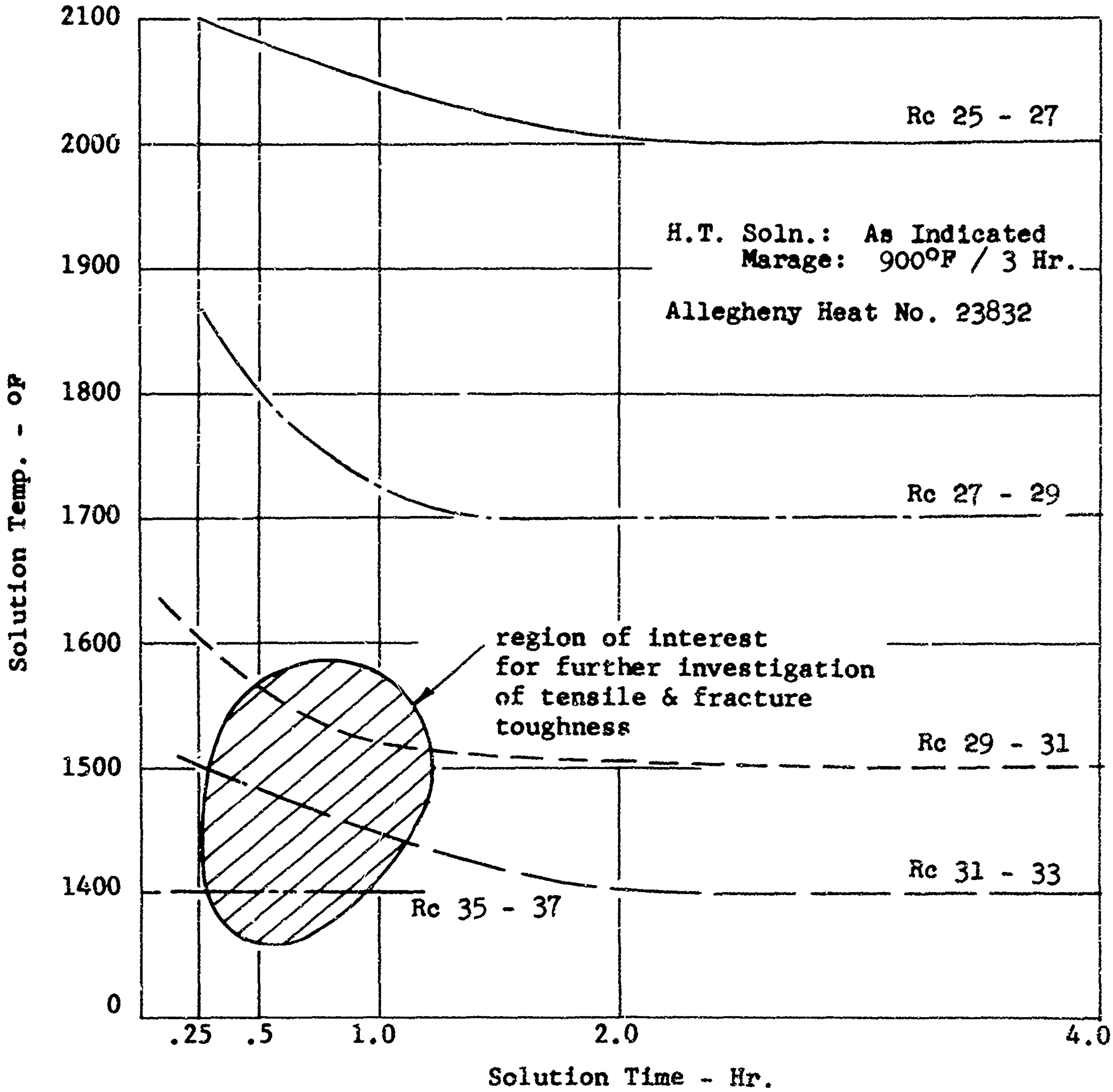


Figure 32

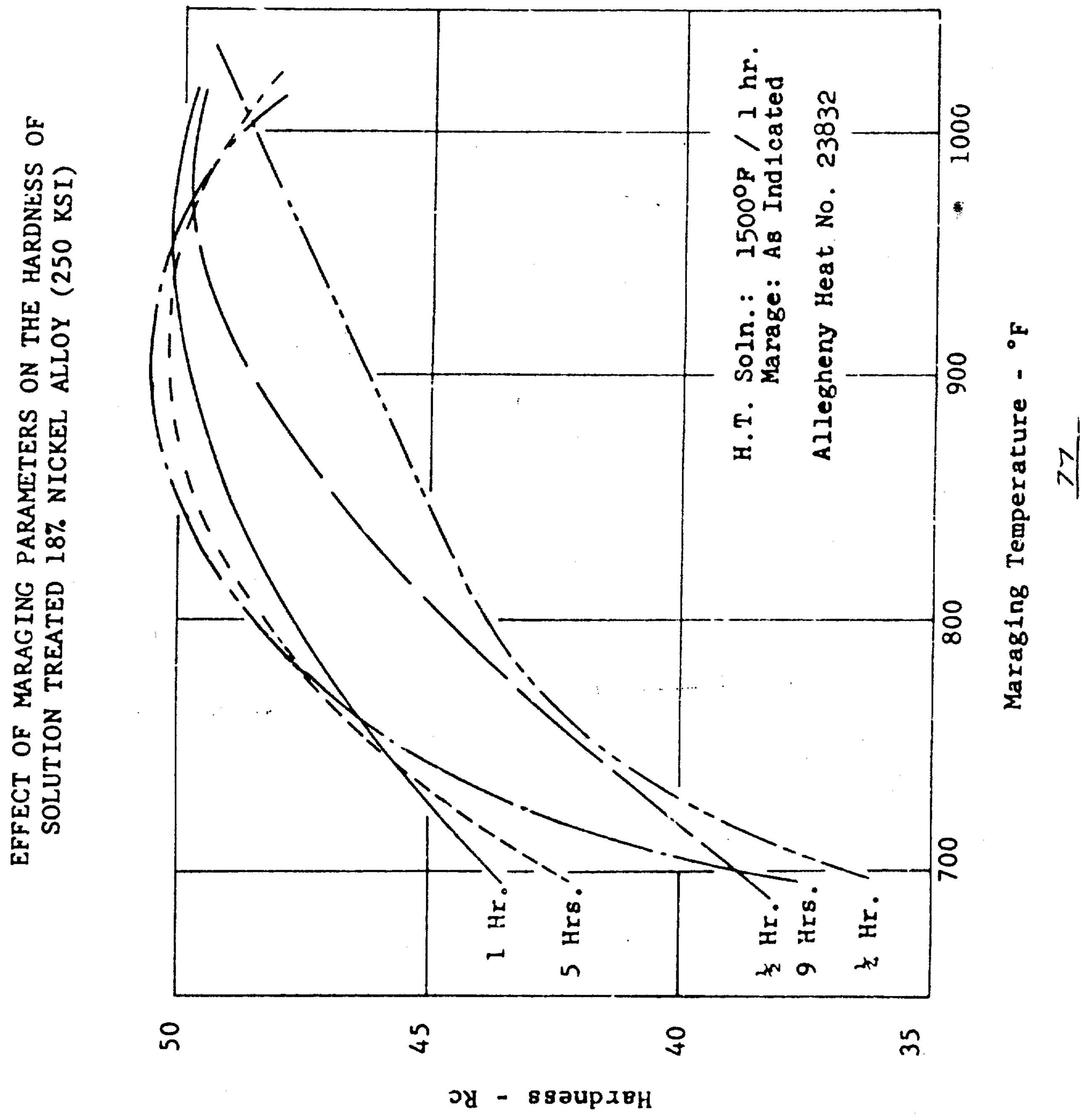

EFFECT OF MARAGING PARAMETERS ON THE HARDNESS OF
SOLUTION TREATED 18% NICKEL ALLOY (250 KSI)
H.T. Soln.: 1500°F / 1 hr.
Marage: As Indicated
Allegheny Heat No. 23832
1 Hr.
5 Hrs.
½ Hr.
9 Hrs.
¼ Hr.
Hardness - Rc
50
45
40
35
700
800
900
1000
Maraging Temperature - °F
77

Figure 33

EFFECT OF SOLUTION TREATING TEMPERATURE ON THE
LONGITUDINAL PROPERTIES OF 18% NICKEL ALLOY (250 KSI)

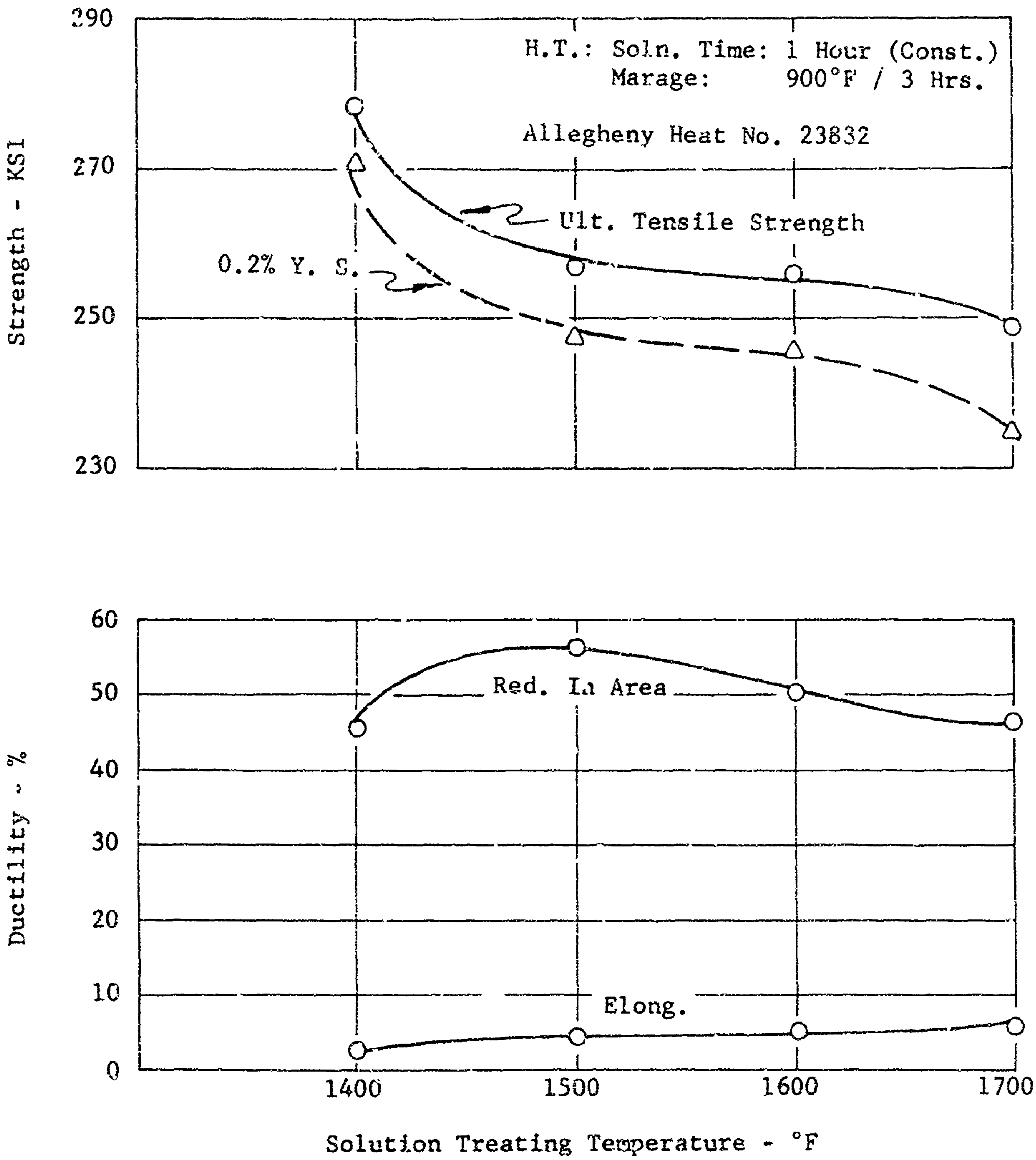


Figure 34

EFFECT OF SOLUTION TREATING TIME ON LONGITUDINAL TENSILE PROPERTIES OF 18% NICKEL ALLOY (250 KSI)

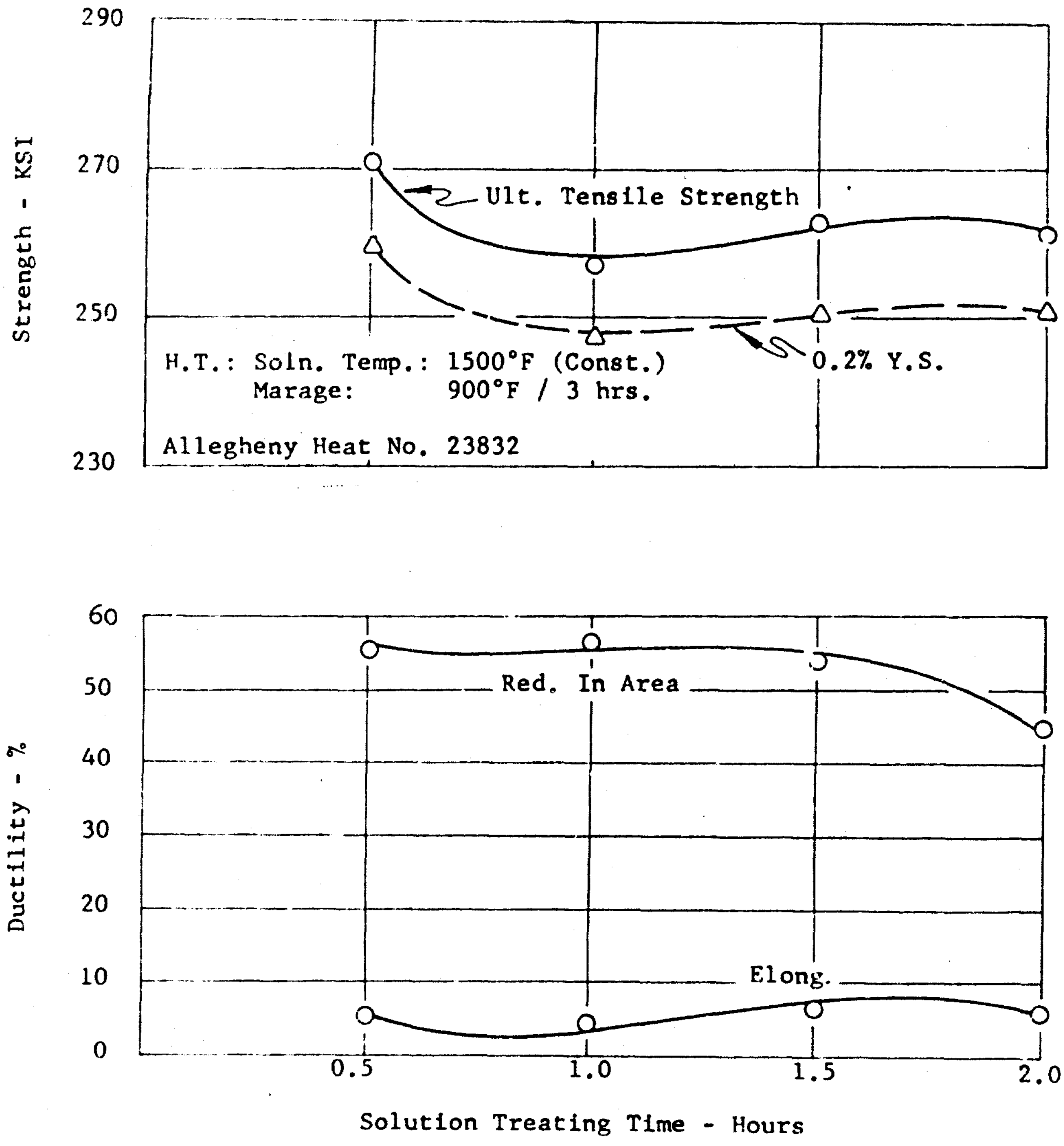


Figure 35

EFFECT OF SOLUTION TREATING TIME ON TRANSVERSE
TENSILE PROPERTIES OF SOLUTION ANNEALED
18% NICKEL ALLOY (250 KSI)

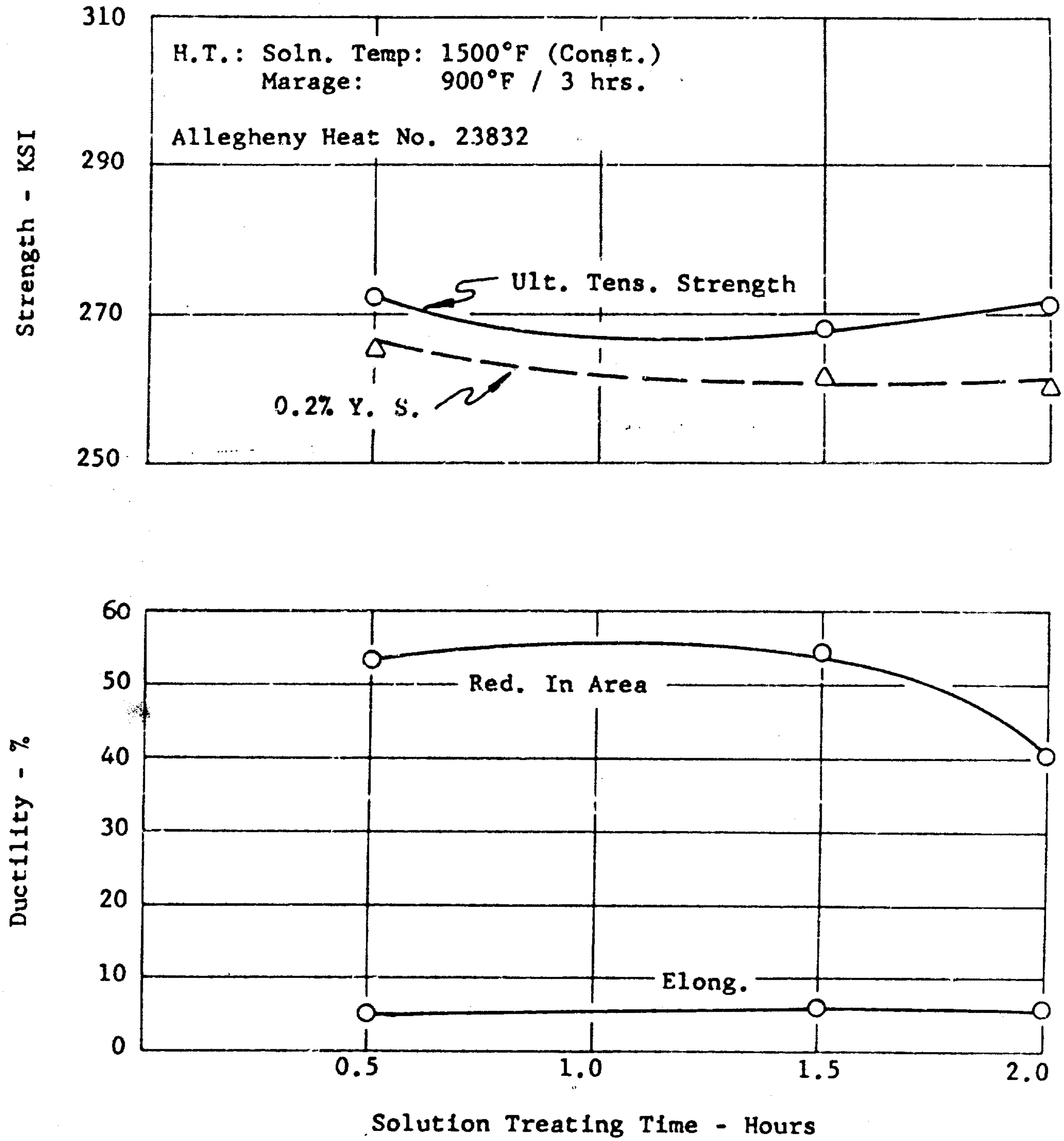


Figure 36

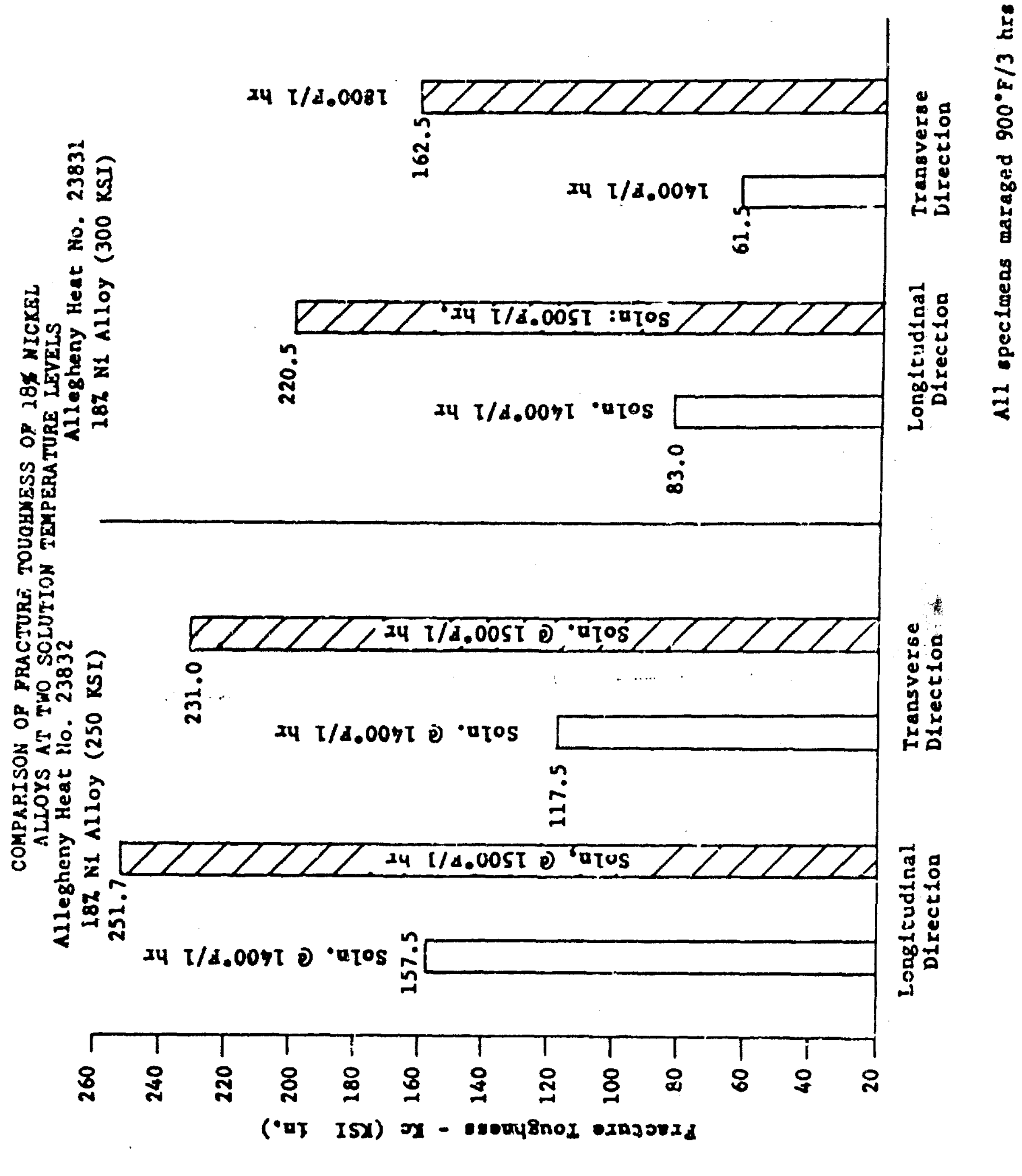

COMPARISON OF FRACTURE TOUGHNESS OF 18% NICKEL
ALLOYS AT TWO SOLUTION TEMPERATURE LEVELS
Allegheny Heat No. 23832
18% Ni Alloy (250 KSI)
Allegheny Heat No. 23831
18% Ni Alloy (300 KSI)
Fracture Toughness - Kc (KSI √in.)
260
240
220
200
180
160
140
120
100
80
60
40
20
157.5
Soln. @ 1400°F/1 hr
251.7
Soln. @ 1500°F/1 hr
117.5
Soln. @ 1400°F/1 hr
231.0
Soln. @ 1500°F/1 hr
83.0
Soln. 1400°F/1 hr
220.5
Soln: 1500°F/1 hr.
61.5
1400°F/1 hr
162.5
1800°F/1 hr
Longitudinal Direction
Transverse Direction
Longitudinal Direction
Transverse Direction
All specimens maraged 900°F/3 hrs

Figure 37

COMPARISON OF FRACTURE TOUGHNESS OF 18% NICKEL ALLOYS AT TWO SOLUTION TIME LEVELS

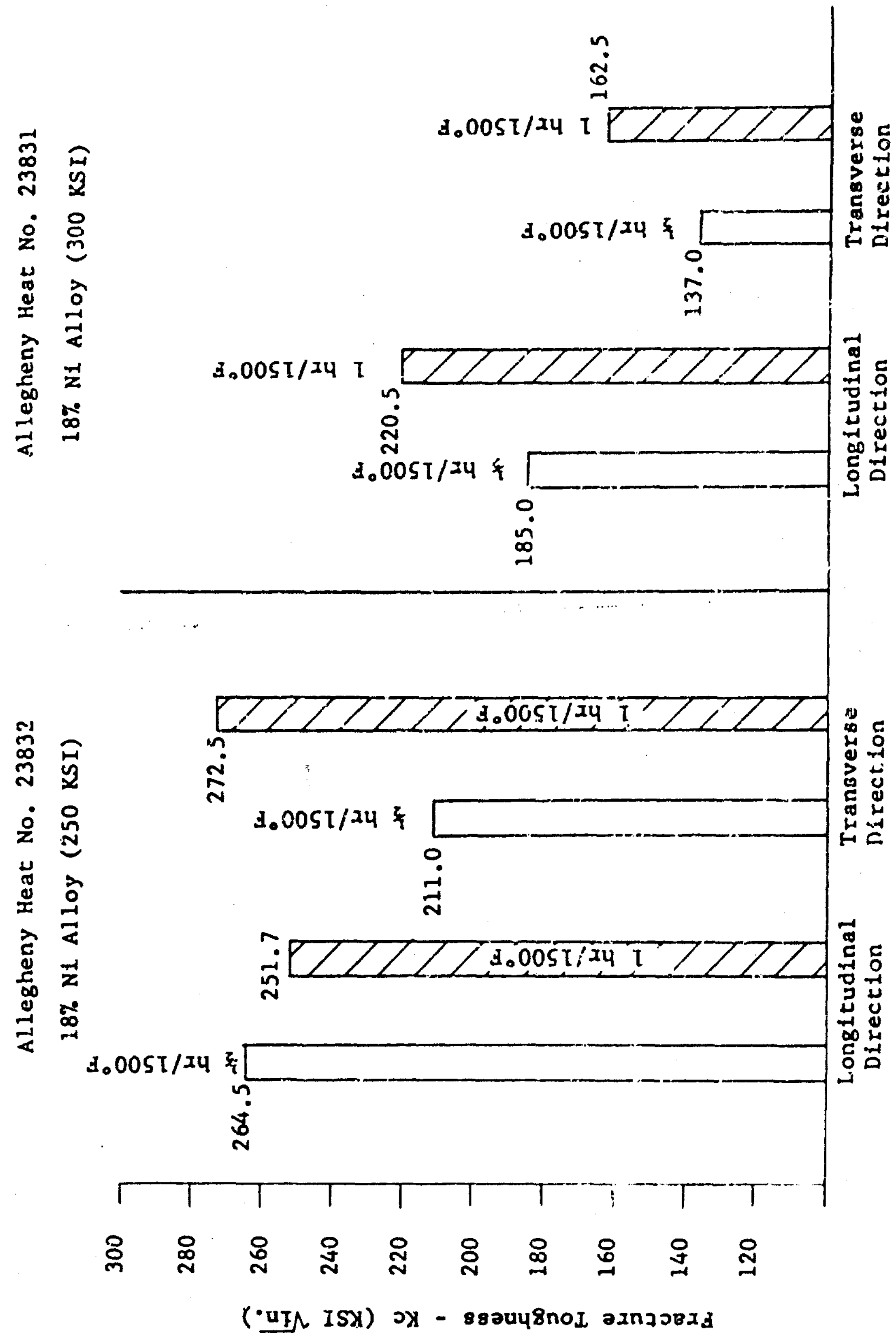
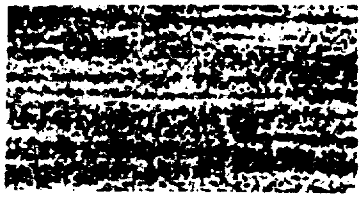


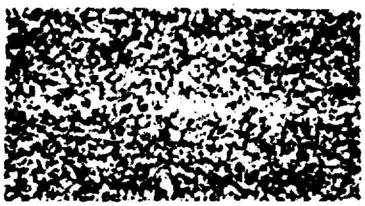
Figure 38

EFFECT OF SOLUTION ANNEALING TEMPERATURE ON MICROSTRUCTURE OF 18% NICKEL ALLOY (250 KSI)

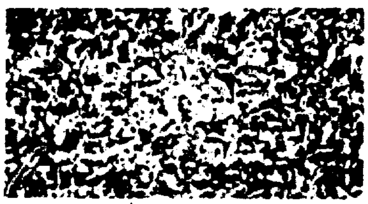
SOLUTION TREATING TEMPERATURE -°F



1400



1500



1700

1900

2100

Figure 39

EFFECT OF MARAGING TREATMENT ON THE LONGITUDINAL TENSILE PROPERTIES OF SOLN. ANNEALED 18% NICKEL ALLOY (250 KSI)

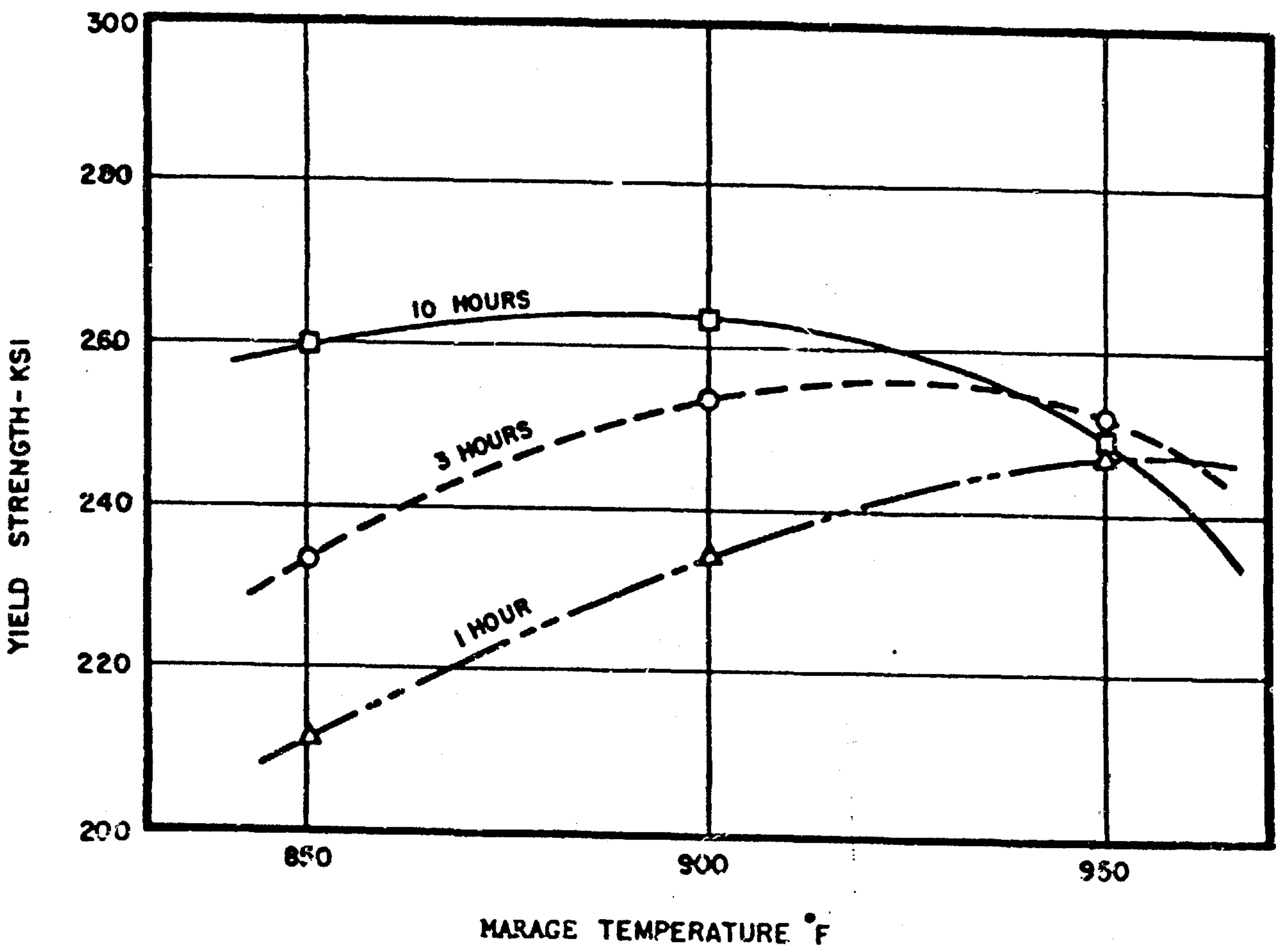


FIG-40

~~Figure 40~~

EFFECT OF MARAGING TREATMENT ON THE
TRANSVERSE TENSILE PROPERTIES OF SOLN. ANNEALED
18% NICKEL ALLOY (250 KSI)

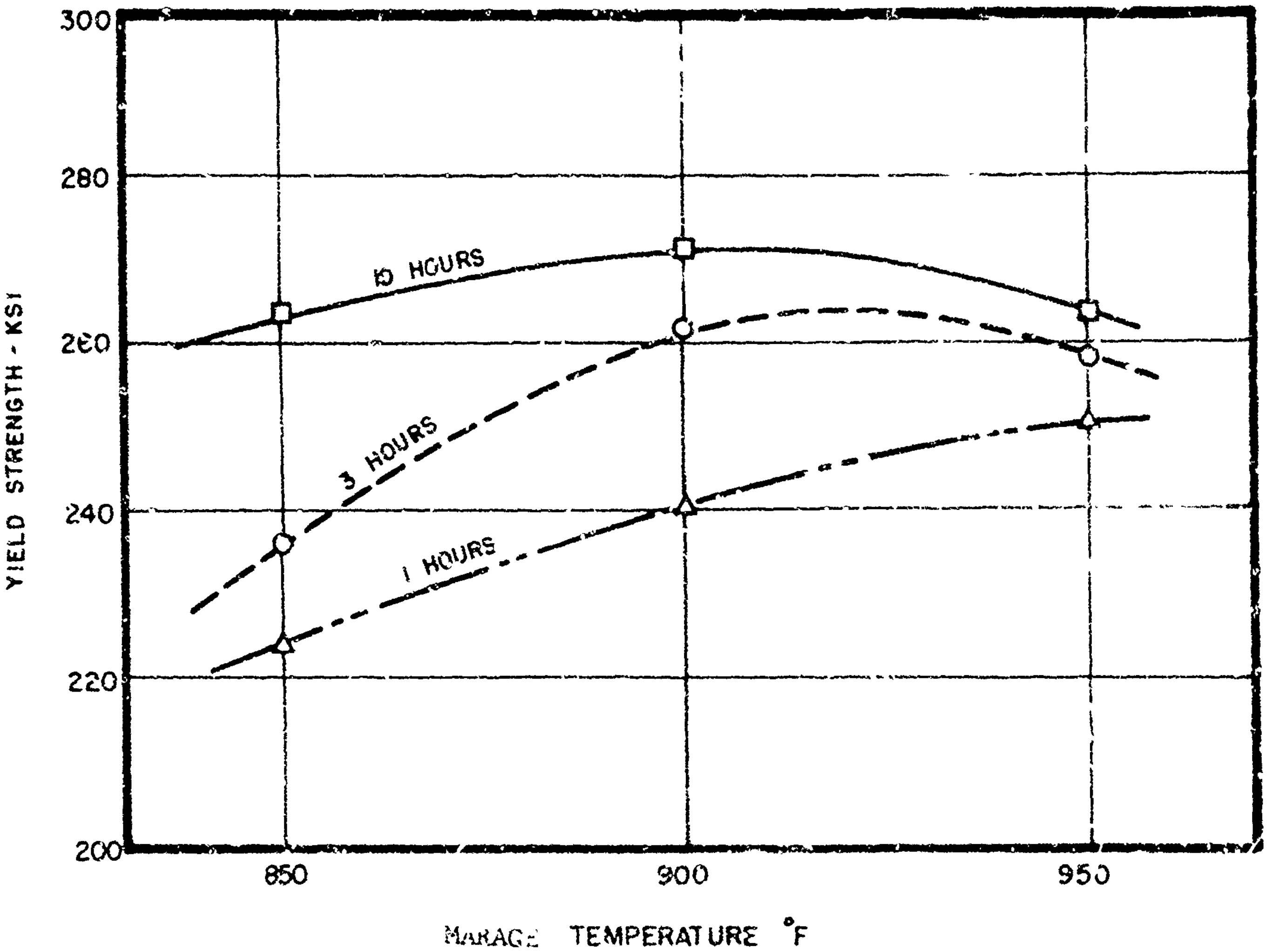
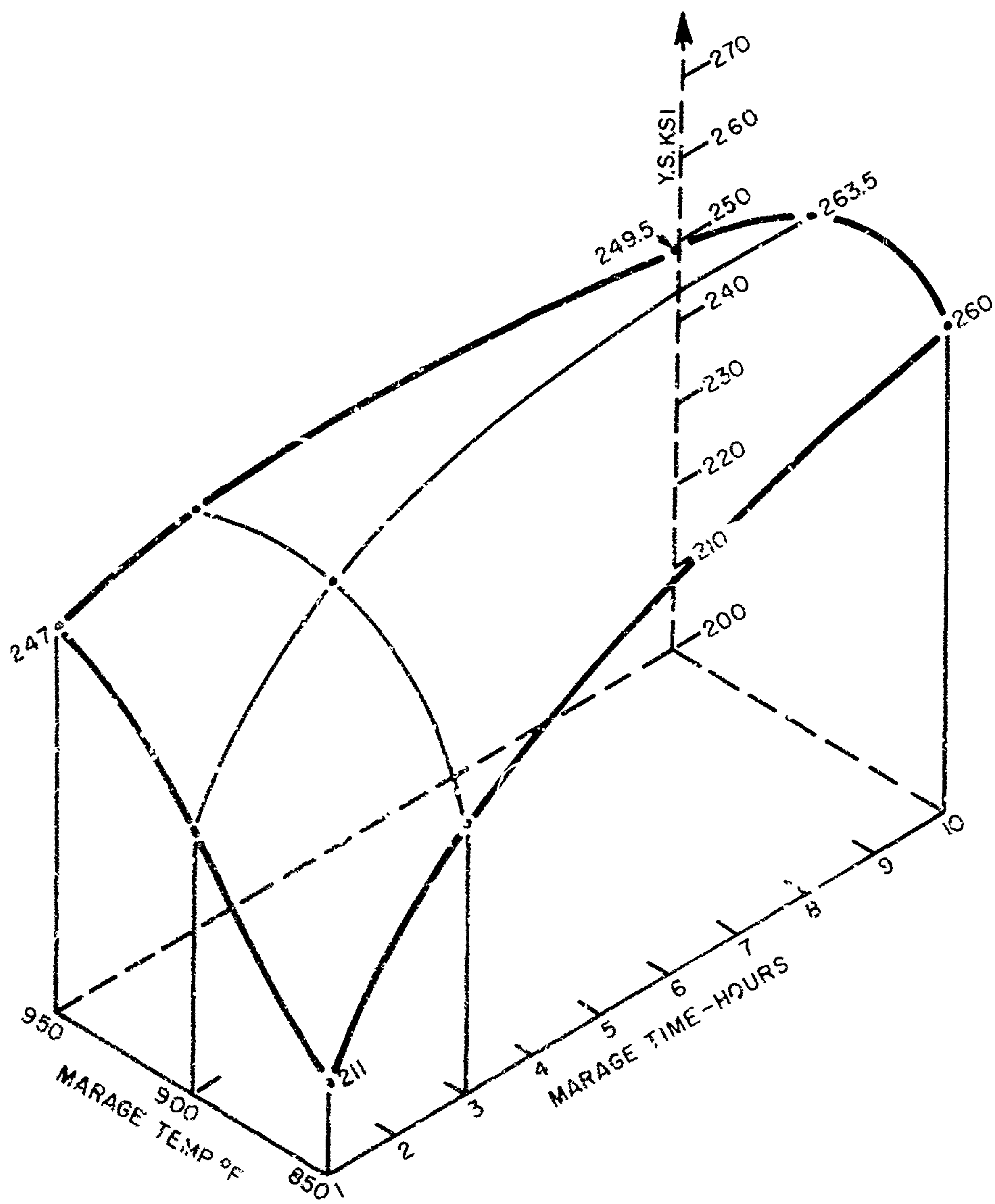


Figure 41

OPTIMIZATION OF LONGITUDINAL YIELD STRENGTH

RESPONSE OF SOLUTION ANNEALED 18% NICKEL ALLOY (250 KSI)



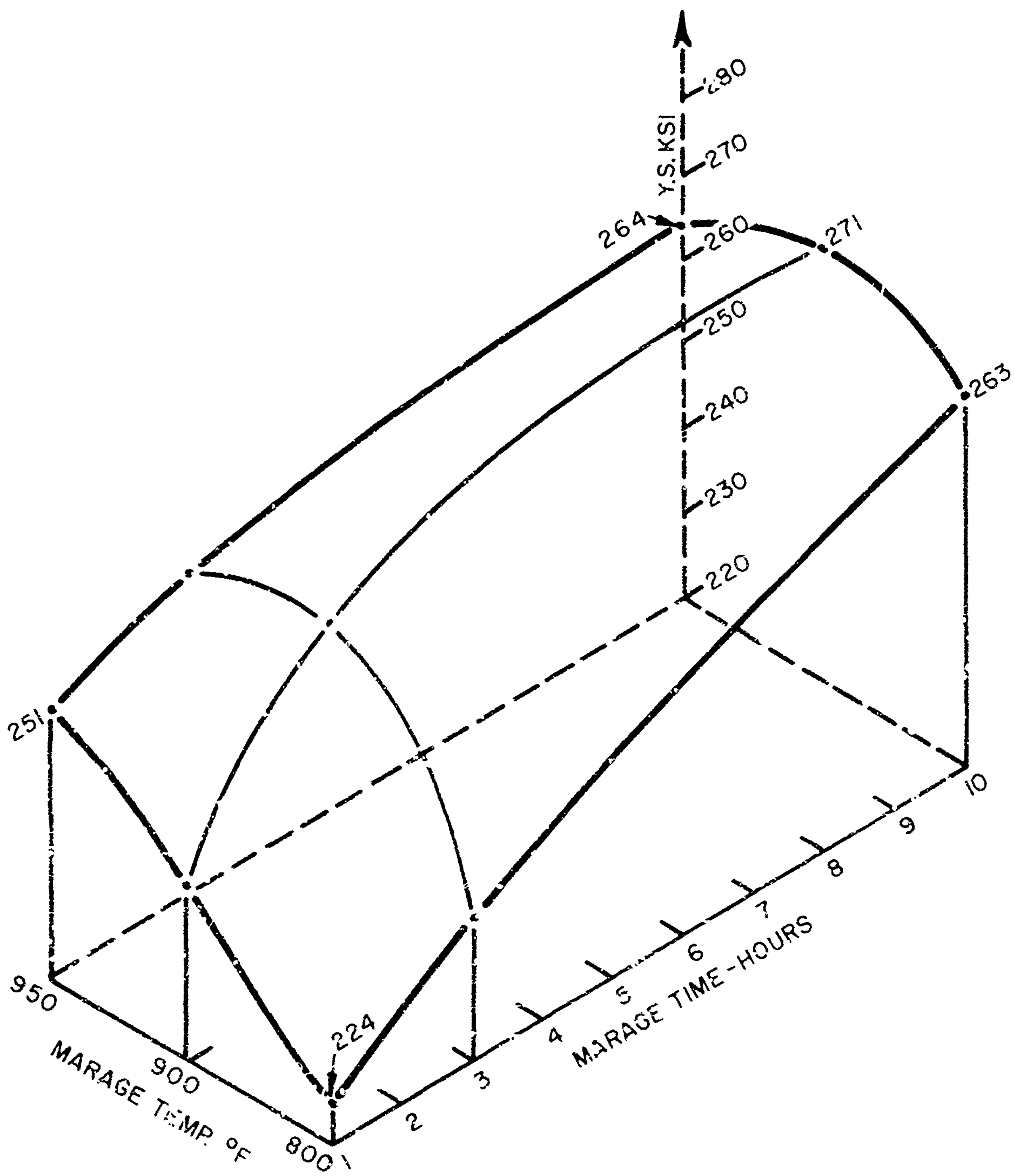
All Specimens Soln. Annealed: 1500°F / 1 hr. (argon)

Allegheny Heat No. 23832

Figure 42

OPTIMIZATION OF TRANSVERSE YIELD STRENGTH

RESPONSE OF SOLUTION ANNEALED 18% NICKEL ALLOY (250 KSI)



All Specimens Soln. Annealed: 1500°F / 1 hr. (argon)

Allegheny Heat No. 23832

Figure 43

EFFECT OF COLD WORK, MARAGING TIME, AND MARAGING TEMPERATURE ON THE LONGITUDINAL YIELD STRENGTH OF 18% NICKEL ALLOY (250 KSI)

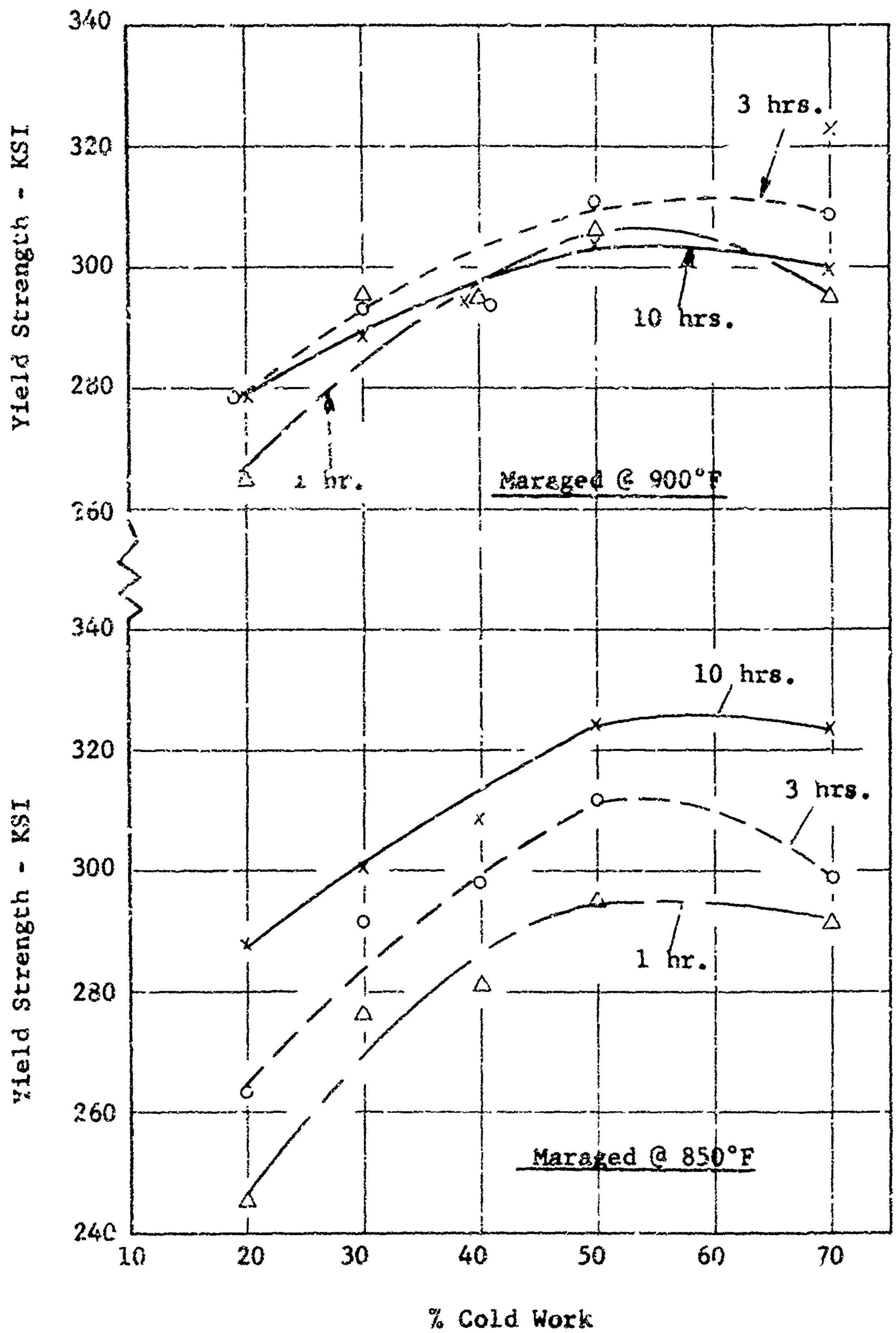


Figure 44

EFFECT OF COLD WORK, MARAGING TIME, AND MARAGING TEMPERATURE ON THE TRANSVERSE YIELD STRENGTH OF 18% NICKEL ALLOY (250 KSI)

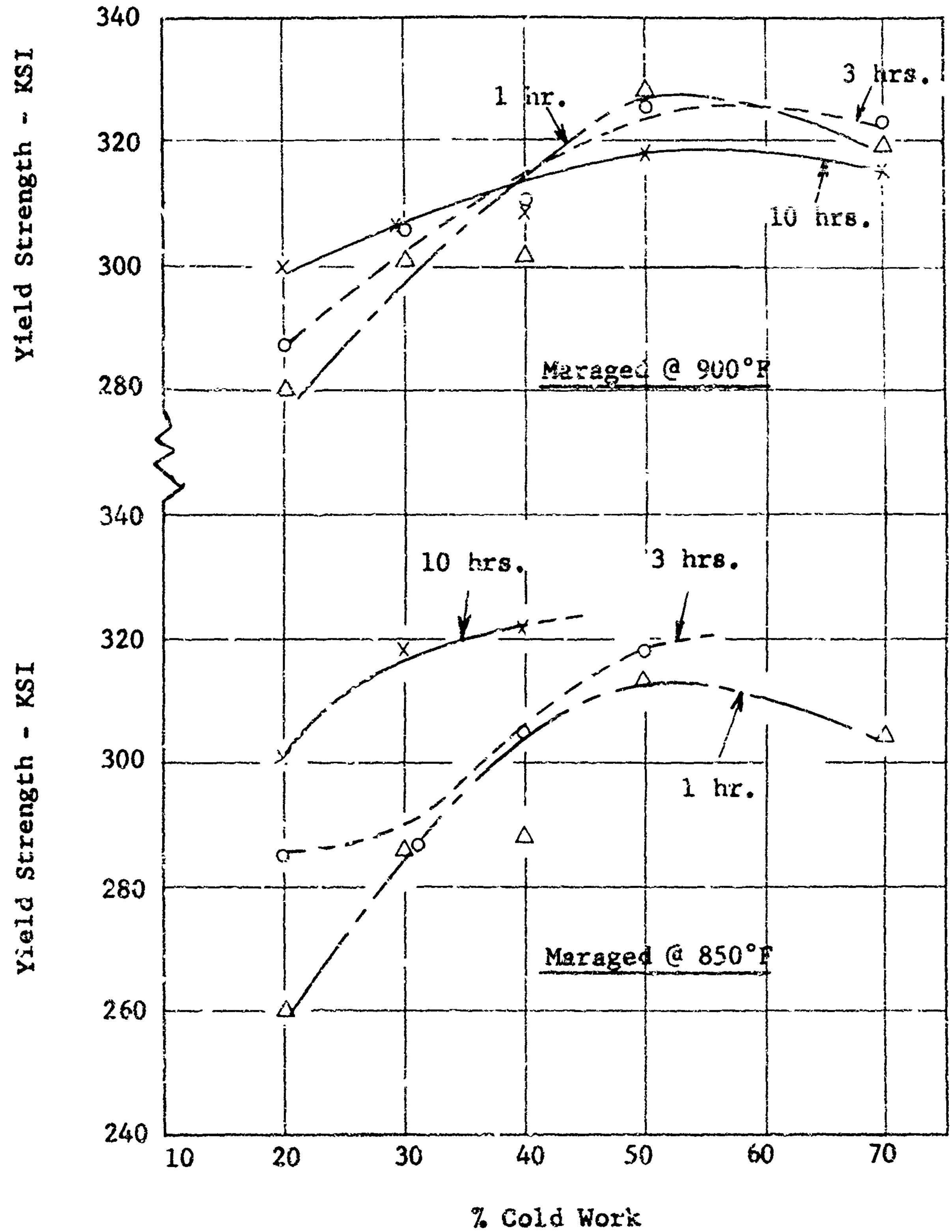


Figure 45

OPTIMIZATION OF LONGITUDINAL YIELD STRENGTH RESPONSE OF COLD WORKED 18% NICKEL ALLOY (250 KSI)

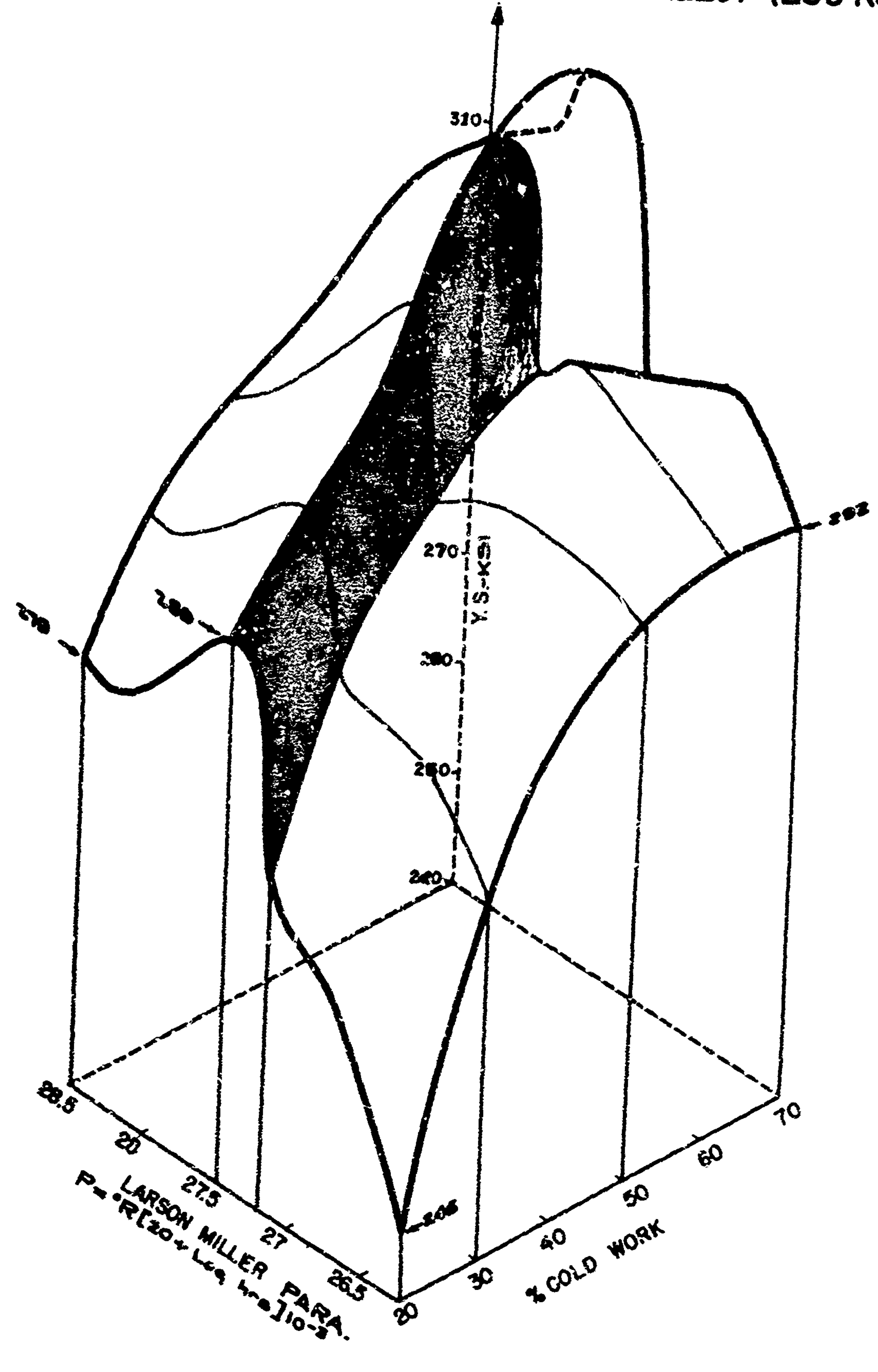


Figure 46

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON
FRACTURE TOUGHNESS OF 18% NI ALLOY (250 KSI)

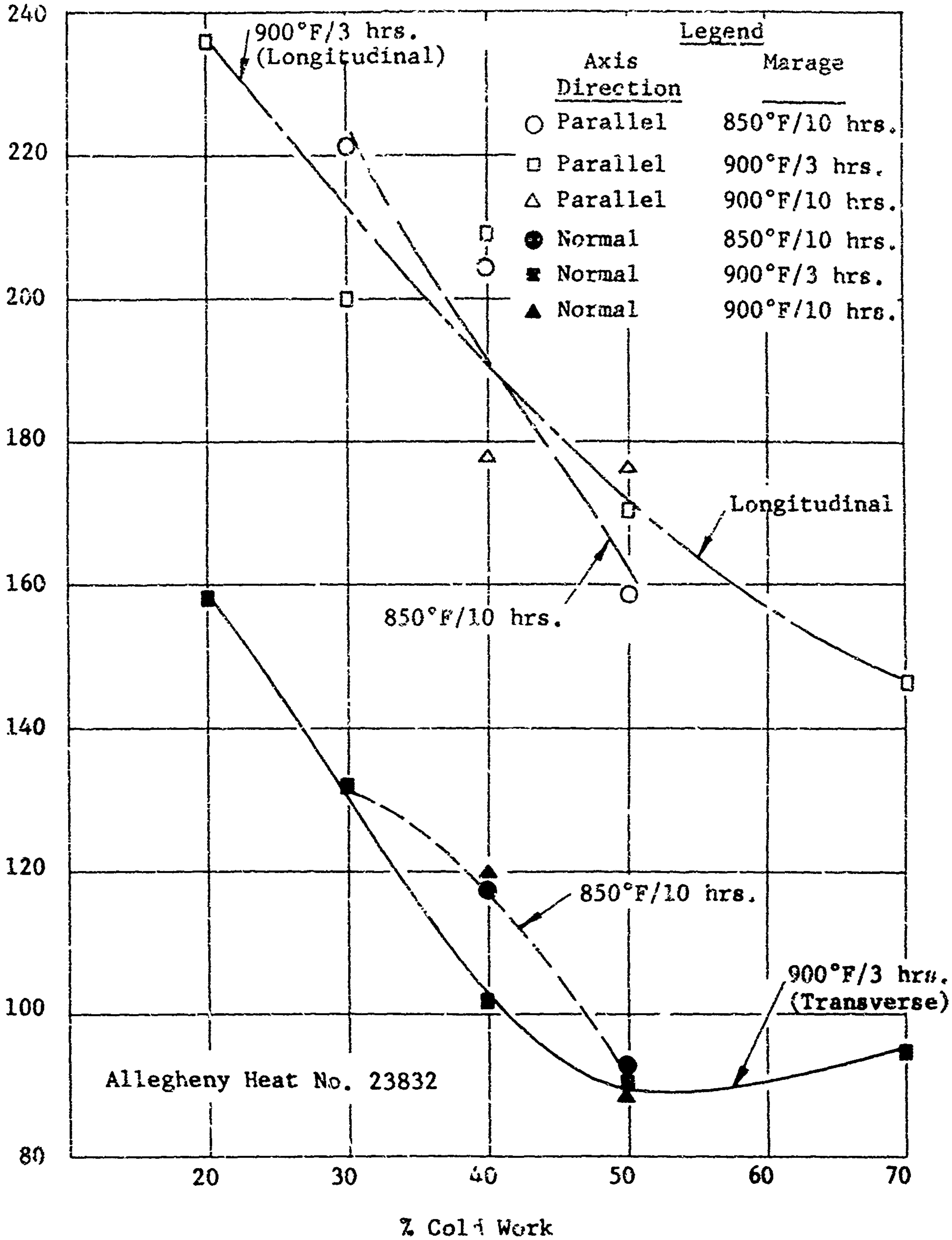


Figure 47

3876

EFFECT OF WARM WORK TEMPERATURE, MARAGING TIME, AND MARAGING TEMPERATURE ON THE LONGITUDINAL YIELD STRENGTH OF 18% NICKEL ALLOY (250 KSI)

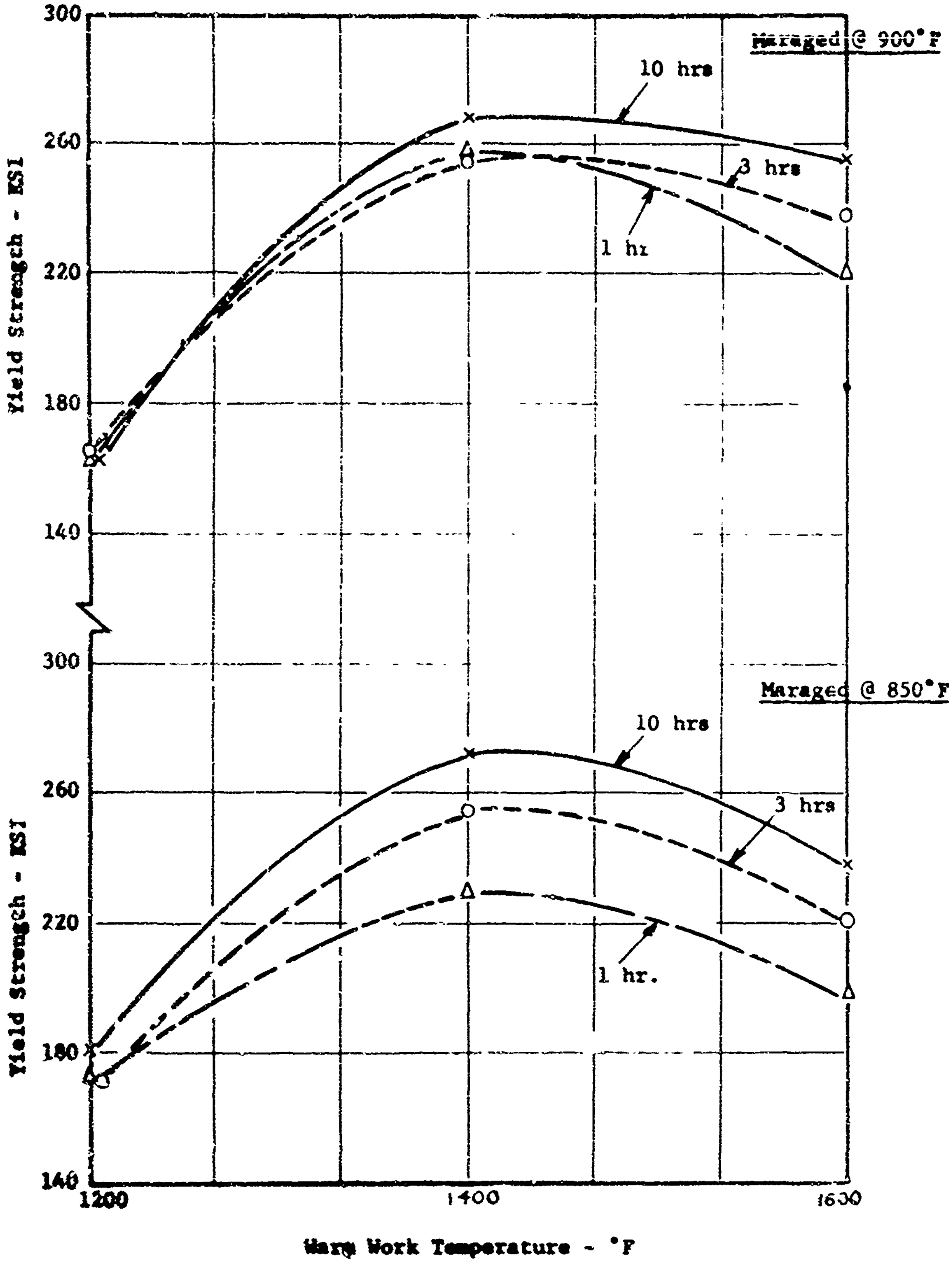


Figure 48

EFFECT OF WARM WORK TEMPERATURE, MARAGING TIME, AND MARAGING TEMPERATURE ON THE TRANSVERSE YIELD STRENGTH OF 18% NICKEL ALLOY (250 KSI)

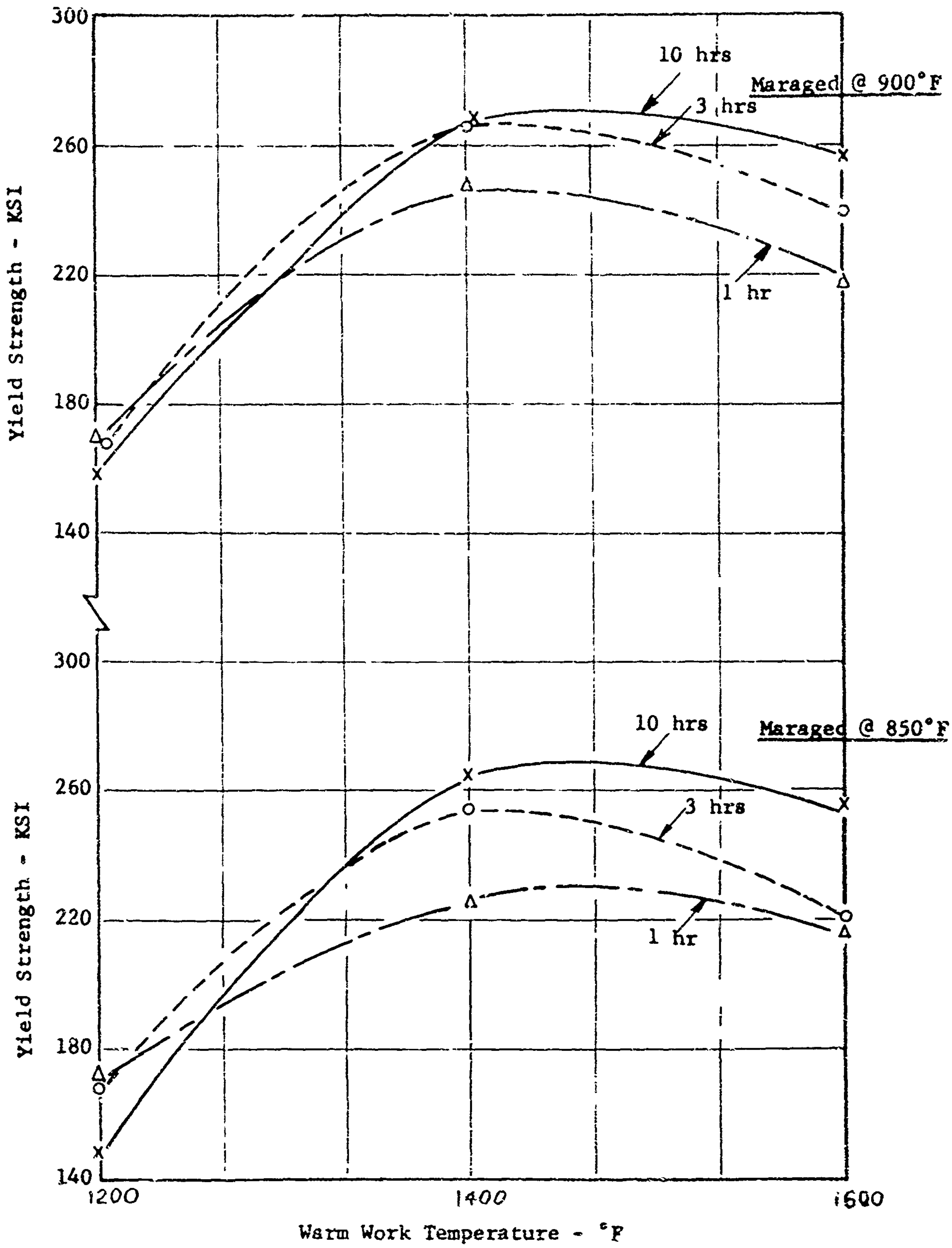


Figure 49

5353

OPTIMIZATION OF LONGITUDINAL YIELD STRENGTH RESPONSE OF WARM WORKED 18% NICKEL ALLOY (250KSI)

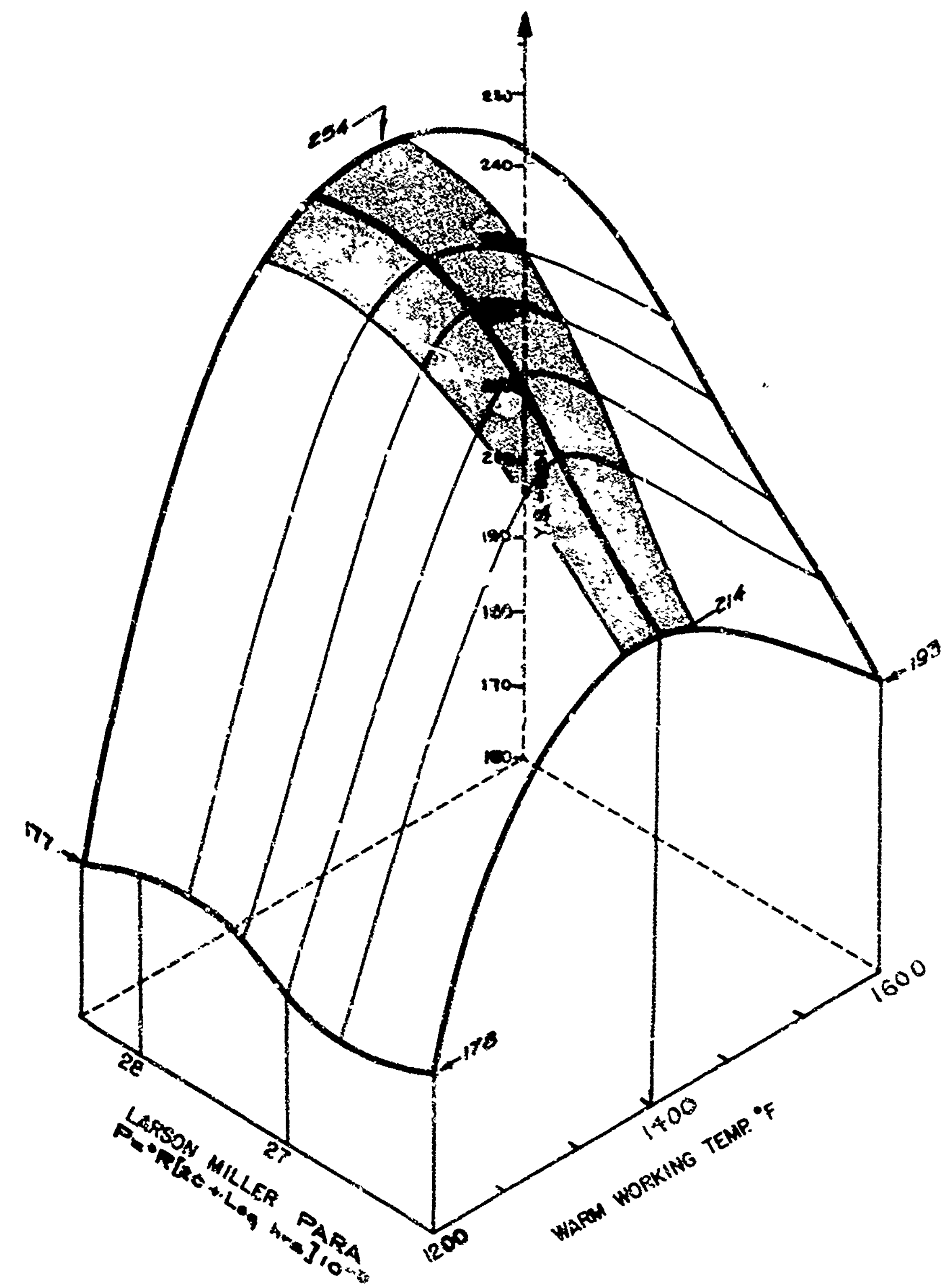


Figure 50

5352

COMPARISON OF FRACTURE TOUGHNESS OF WARM WORKED
18% NICKEL ALLOY (250 And 300 KSI)

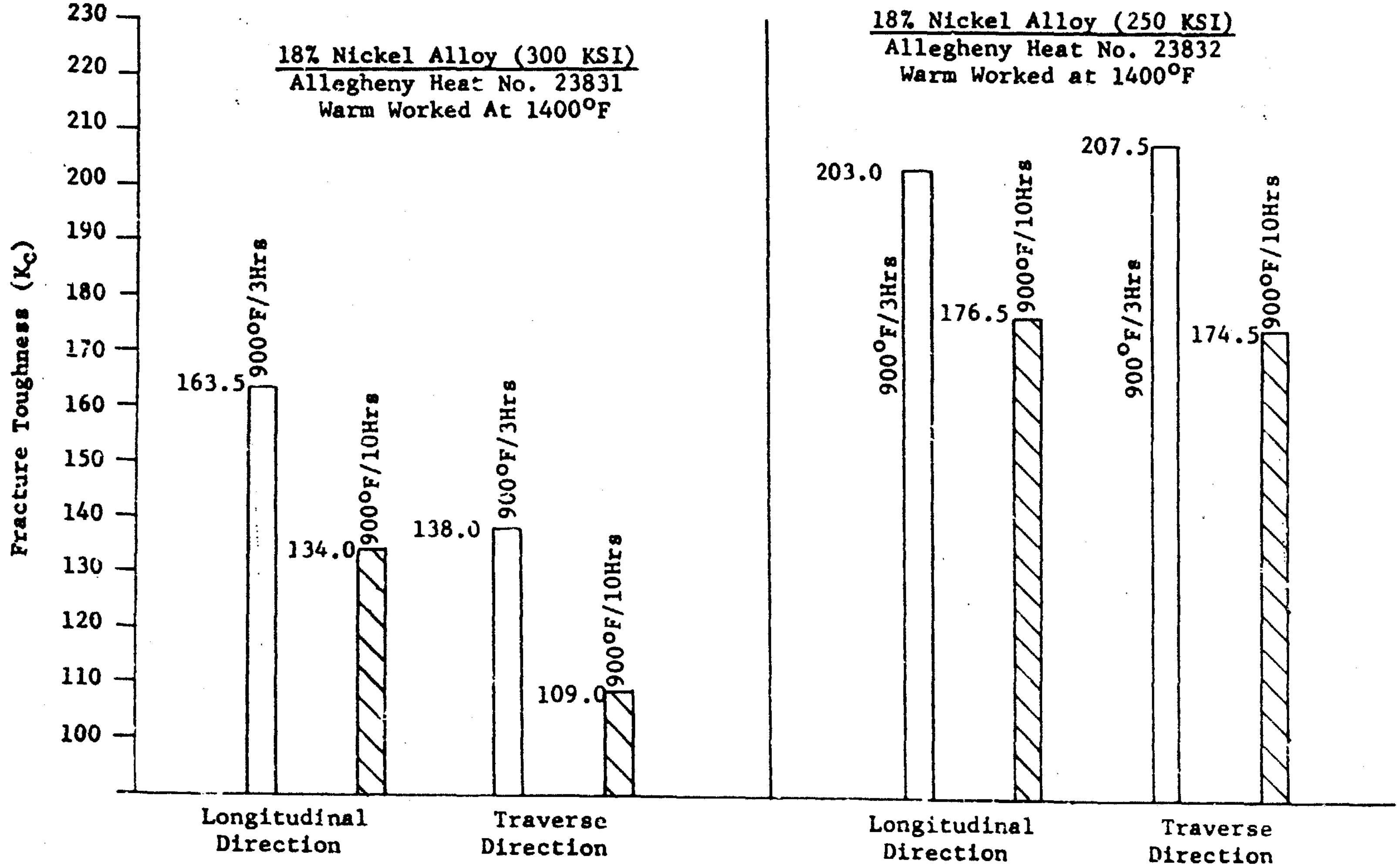


Figure 51

5394

ELEVATED TEMPERATURE TENSILE PROPERTIES OF

SOLUTION ANNEALED 18% NICKEL ALLOY (250 KSI)

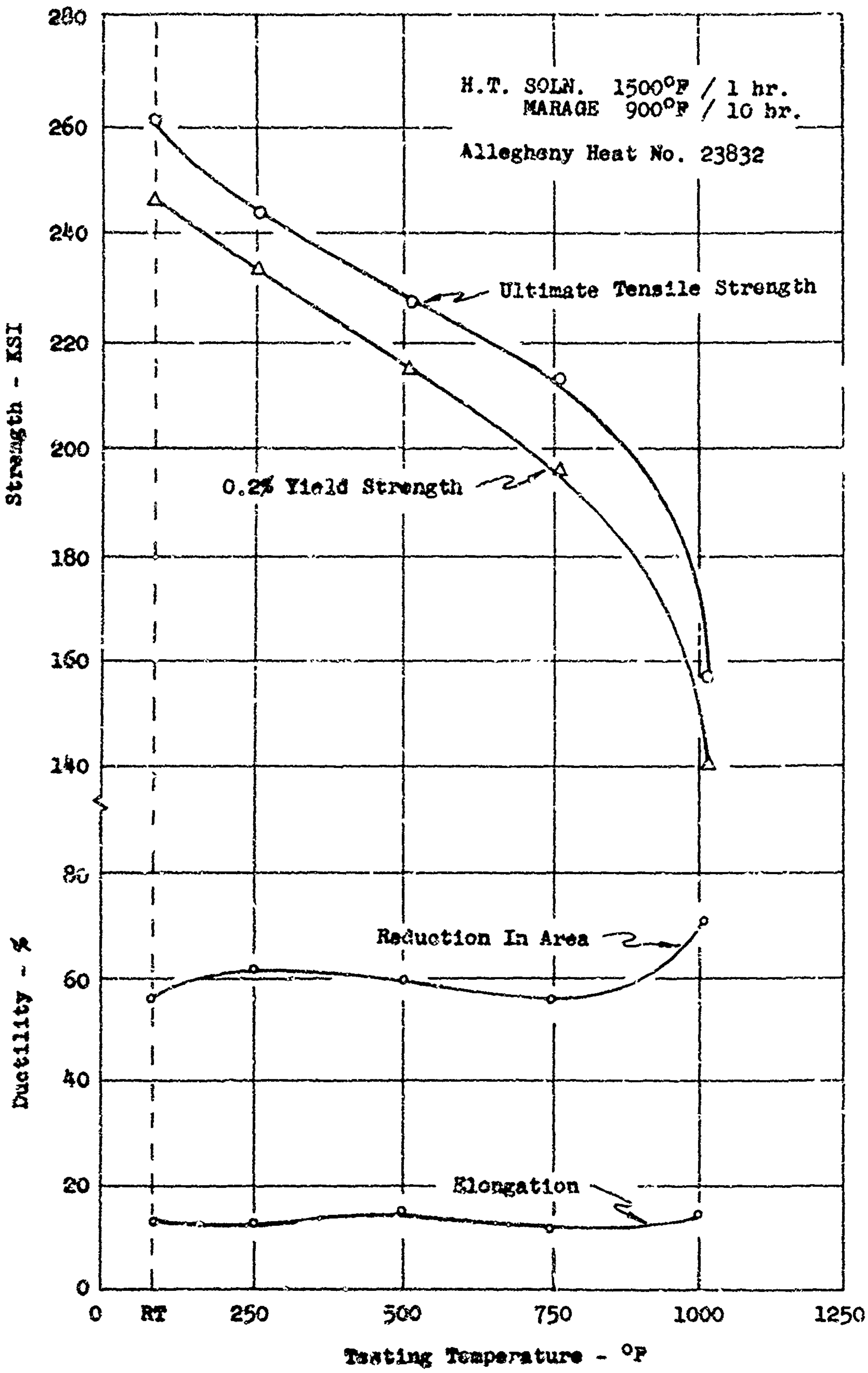


Figure 52

7393

ELEVATED TEMPERATURE PROPERTIES OF
COLD WORKED 18% NICKEL ALLOY (250 KSI)

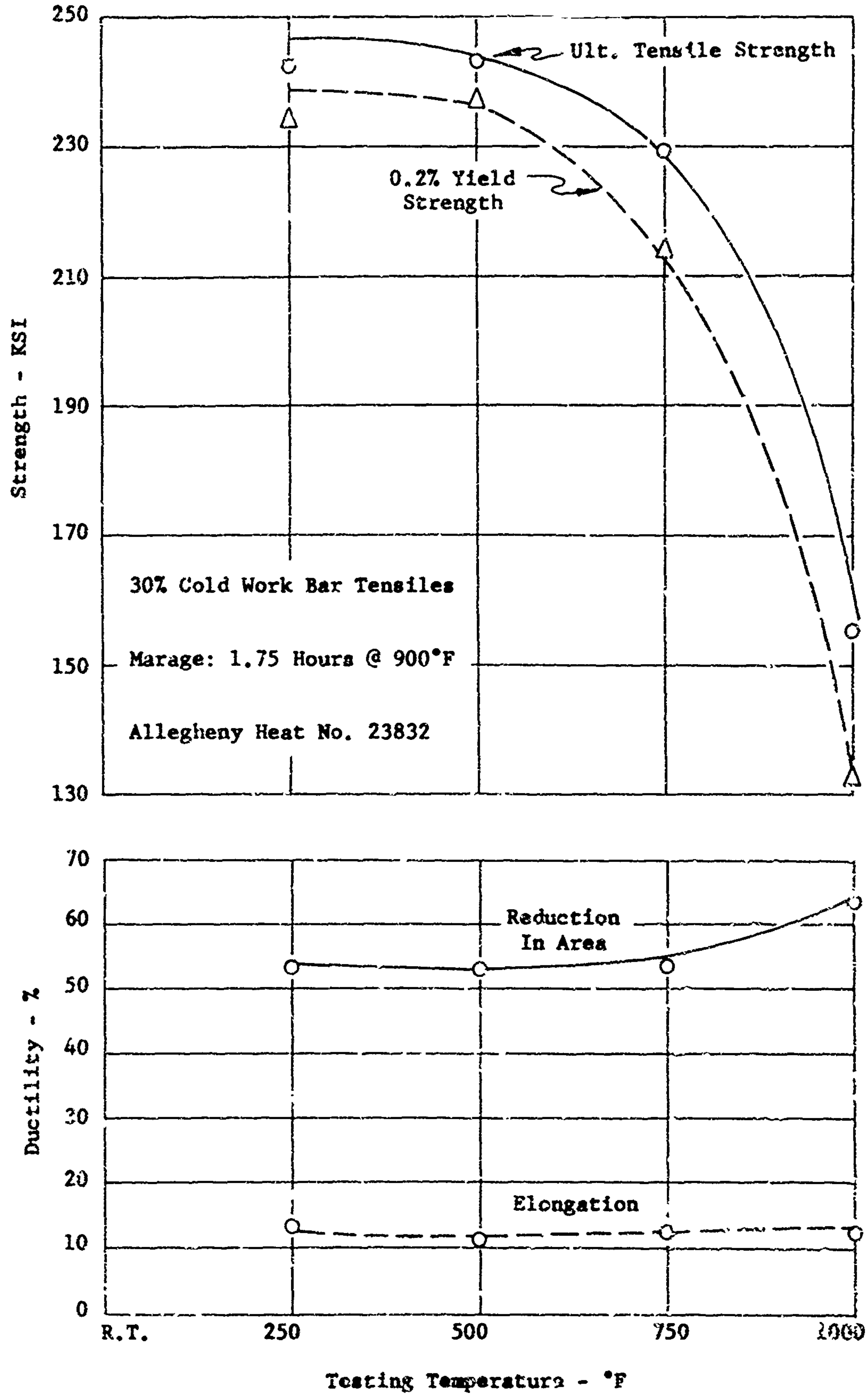


Figure 53

EFFECT OF SOLUTION TIME ON THE ELEVATED TEMPERATURE TENSILE PROPERTIES OF 18% NICKEL ALLOY (250 KSI)

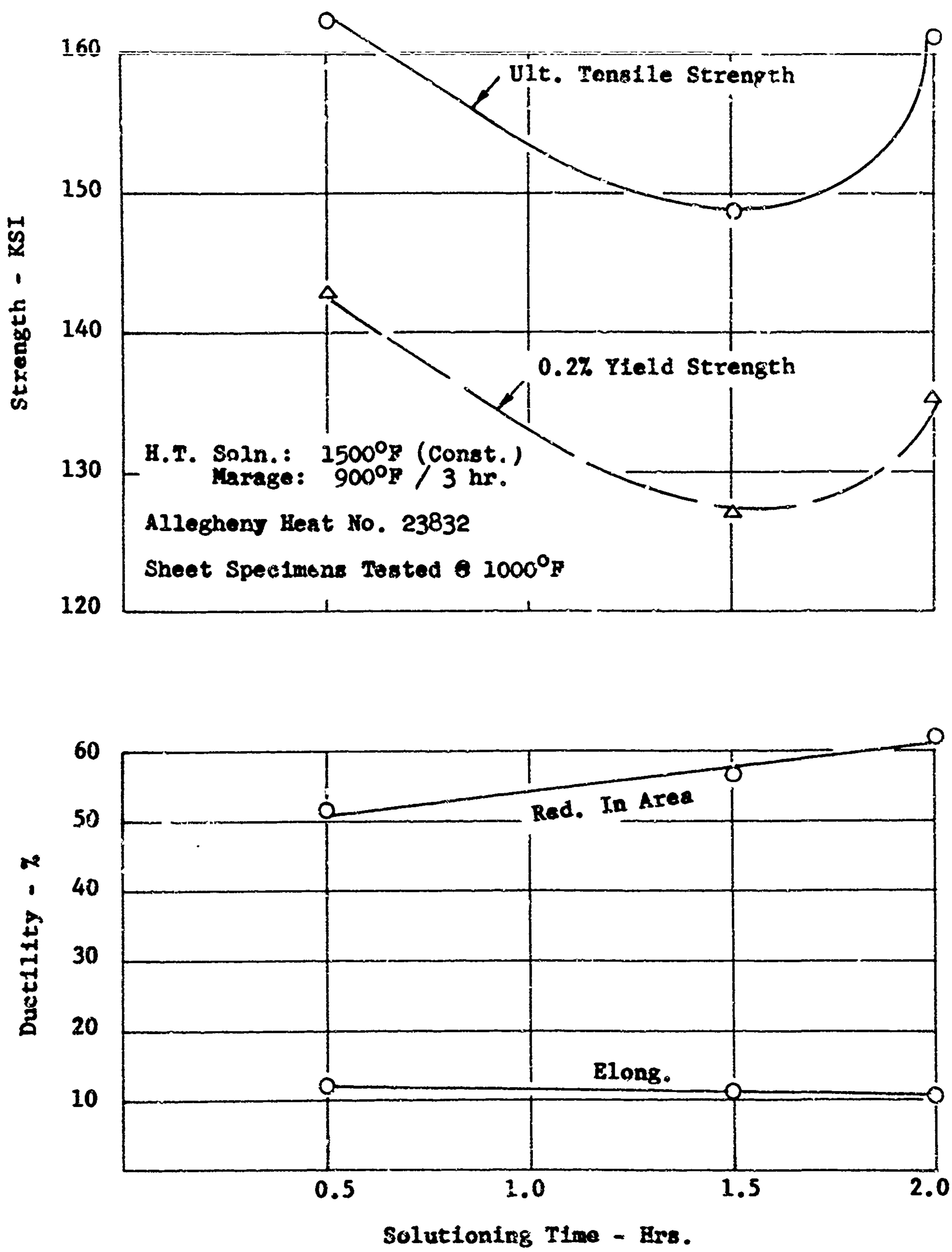
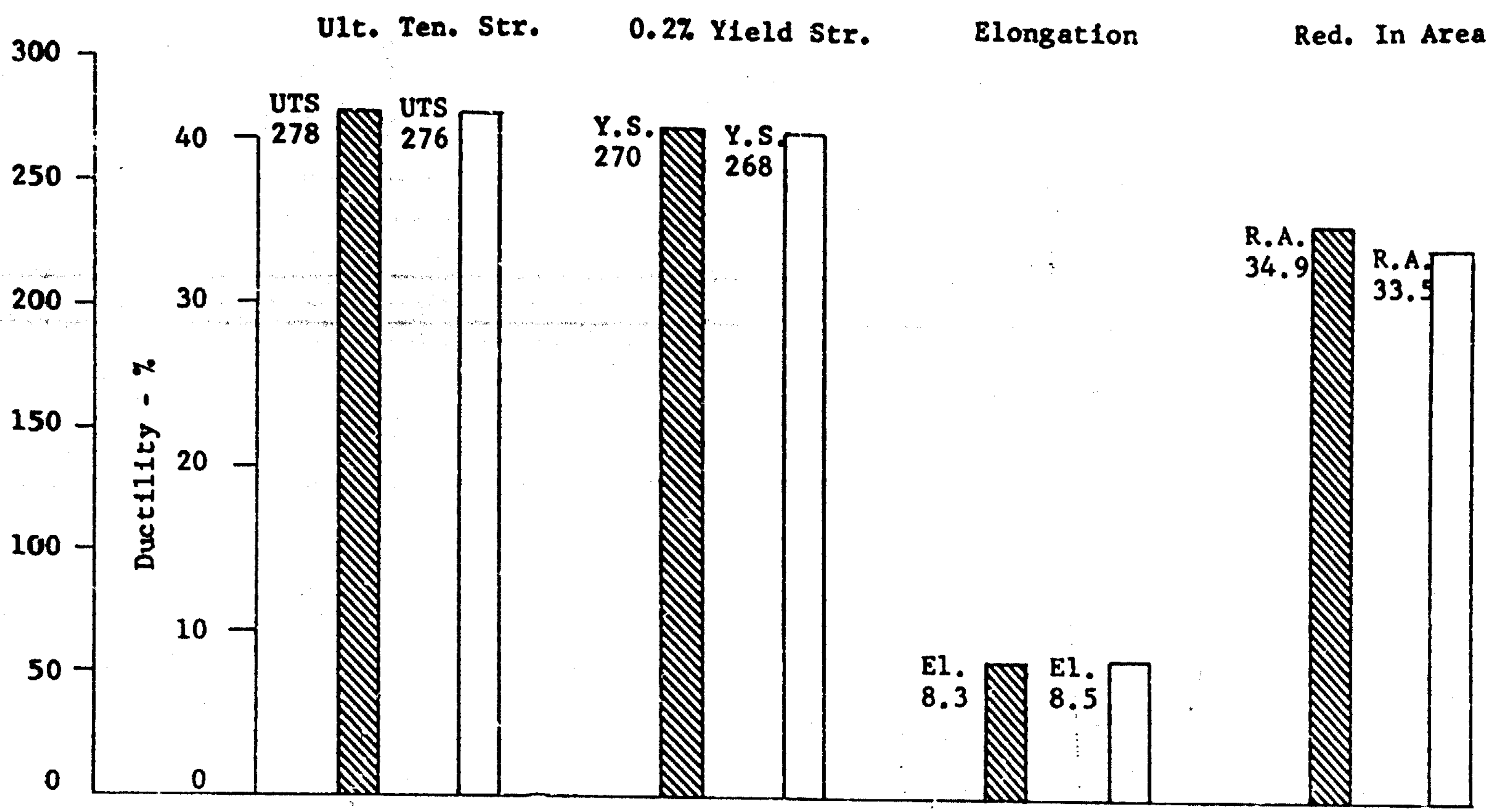


Figure 54

HEAT TREAT RESPONSE OF A THICK SECTION (18% NICKEL ALLOY - 250 KSI)



Cube Dim.: 4½" x 4½" x 5¼"

H.T. Soln.: 1500°F/1 hr.
Marage: 900°F/10 hrs.

1 hr/in. thickness allowed at resp. temperatures

Allegheny Heat No. ⁻⁻332

Tensile Properties of Specimens Machined from Surface of Cube

Tensile Properties of Specimens Machined from Center of Cube

Figure 55

3916

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 18% (250 KSI) MARAGING NICKEL STEEL

LOCATION: VERTICAL-CENTER

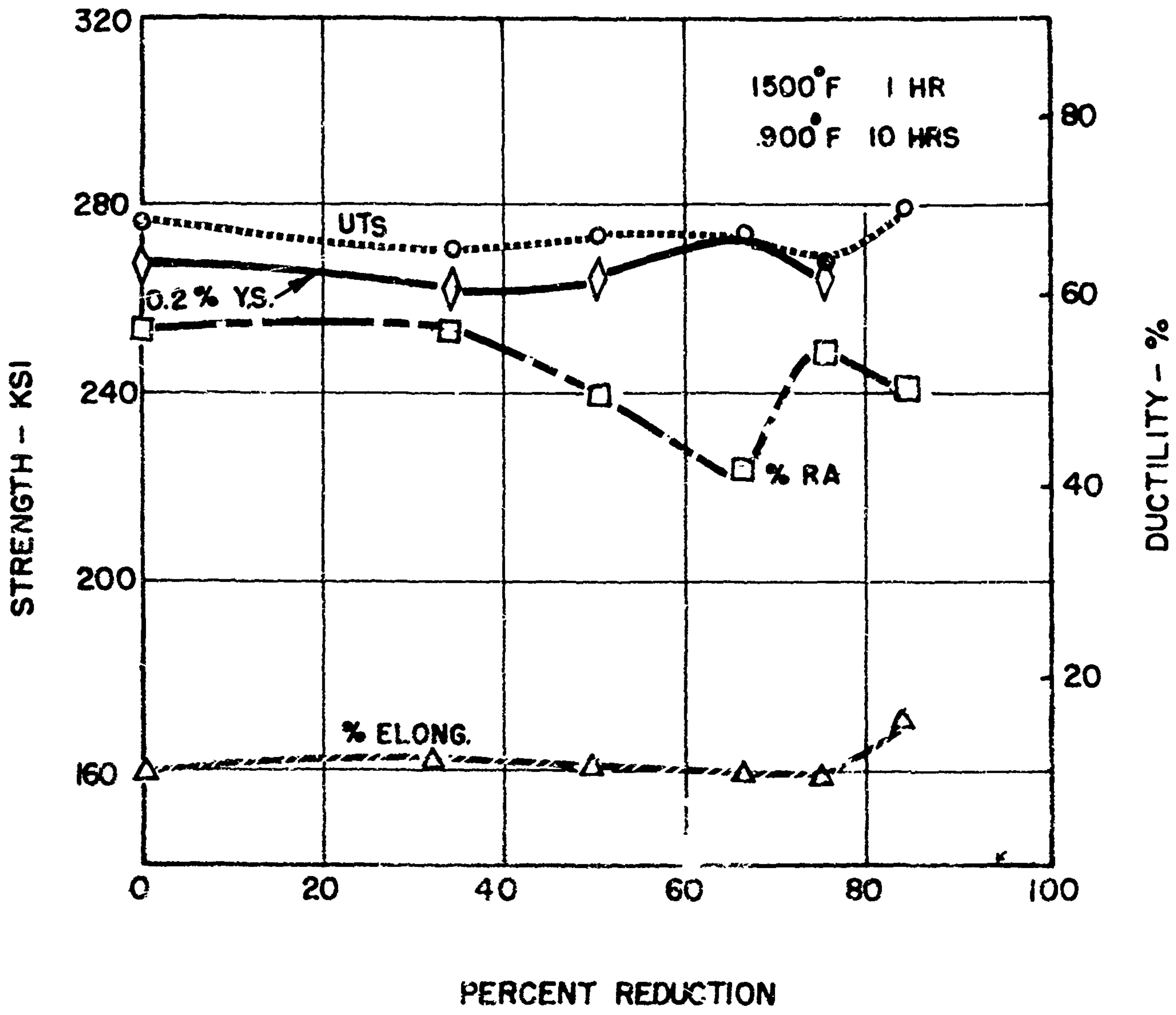


Figure 56

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 18% (250 KSI) MARAGING NICKEL STEEL

LOCATION: VERTICAL-EDGE

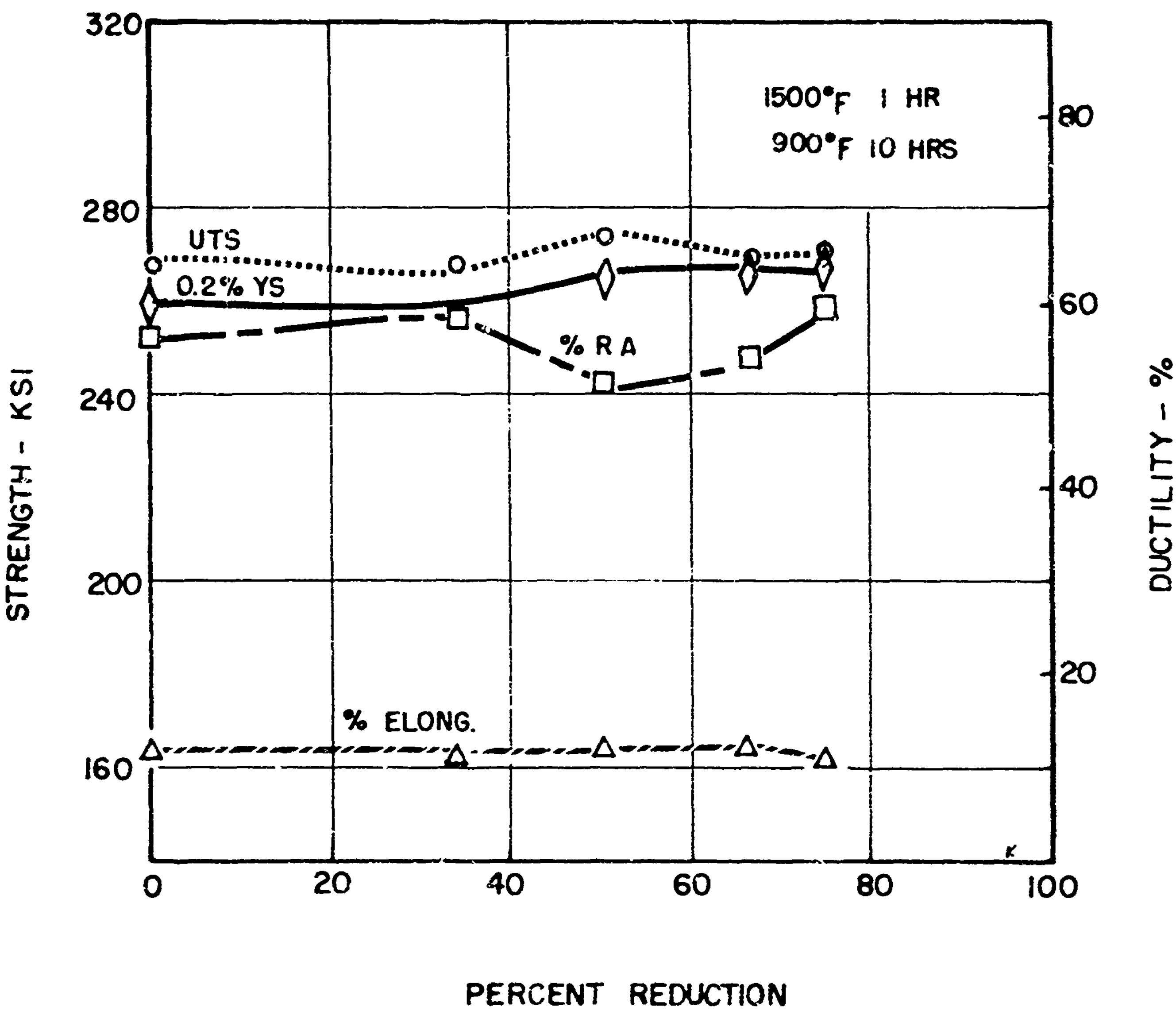


Figure 57

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 18% (250 KSI) MARAGING NICKEL STEEL

LOCATION: HORIZONTAL-CENTER

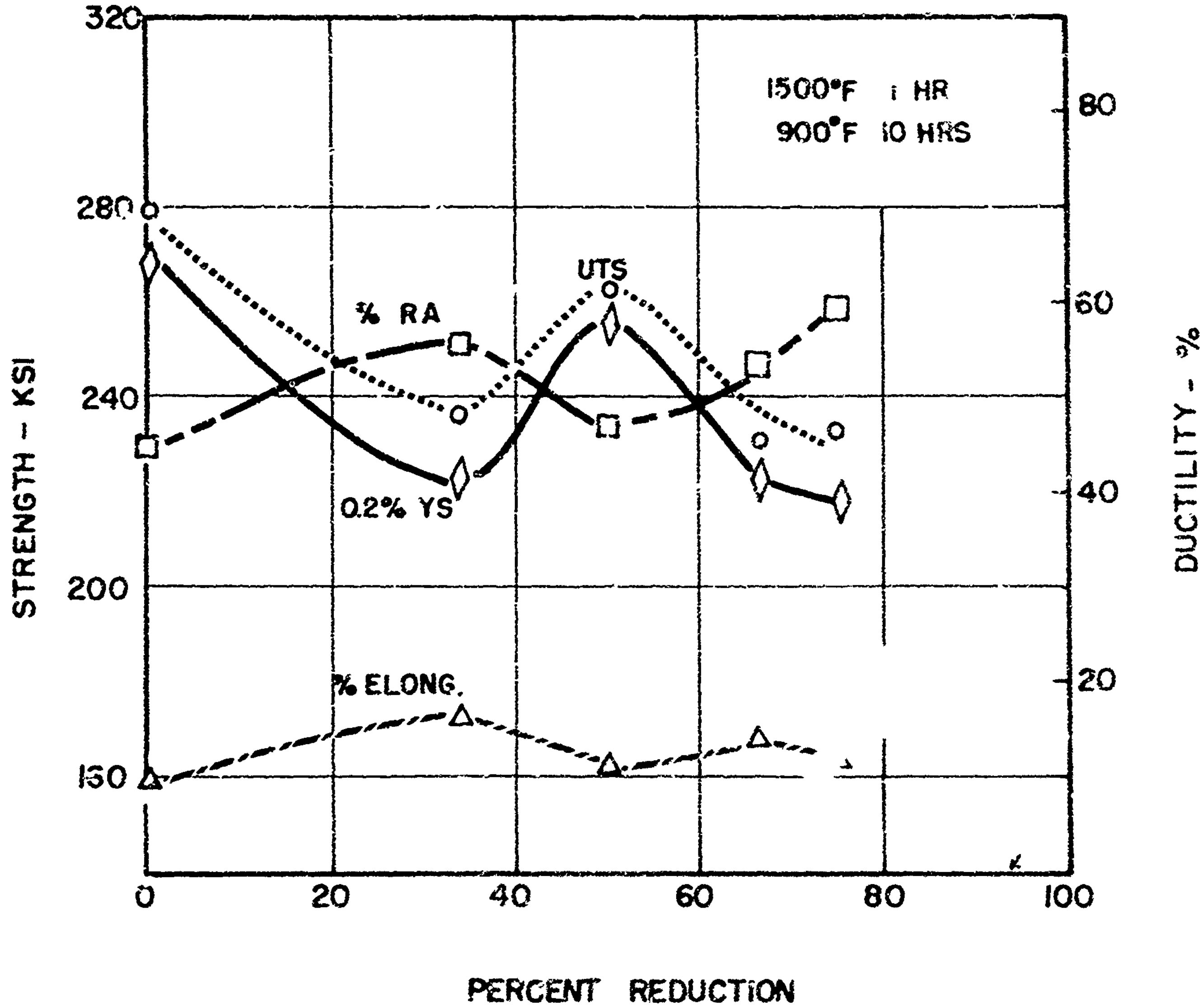


Figure 58

5335

5342

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 18% (250 KSI) MARAGING NICKEL STEEL

LOCATION: HORIZONTAL - EDGE

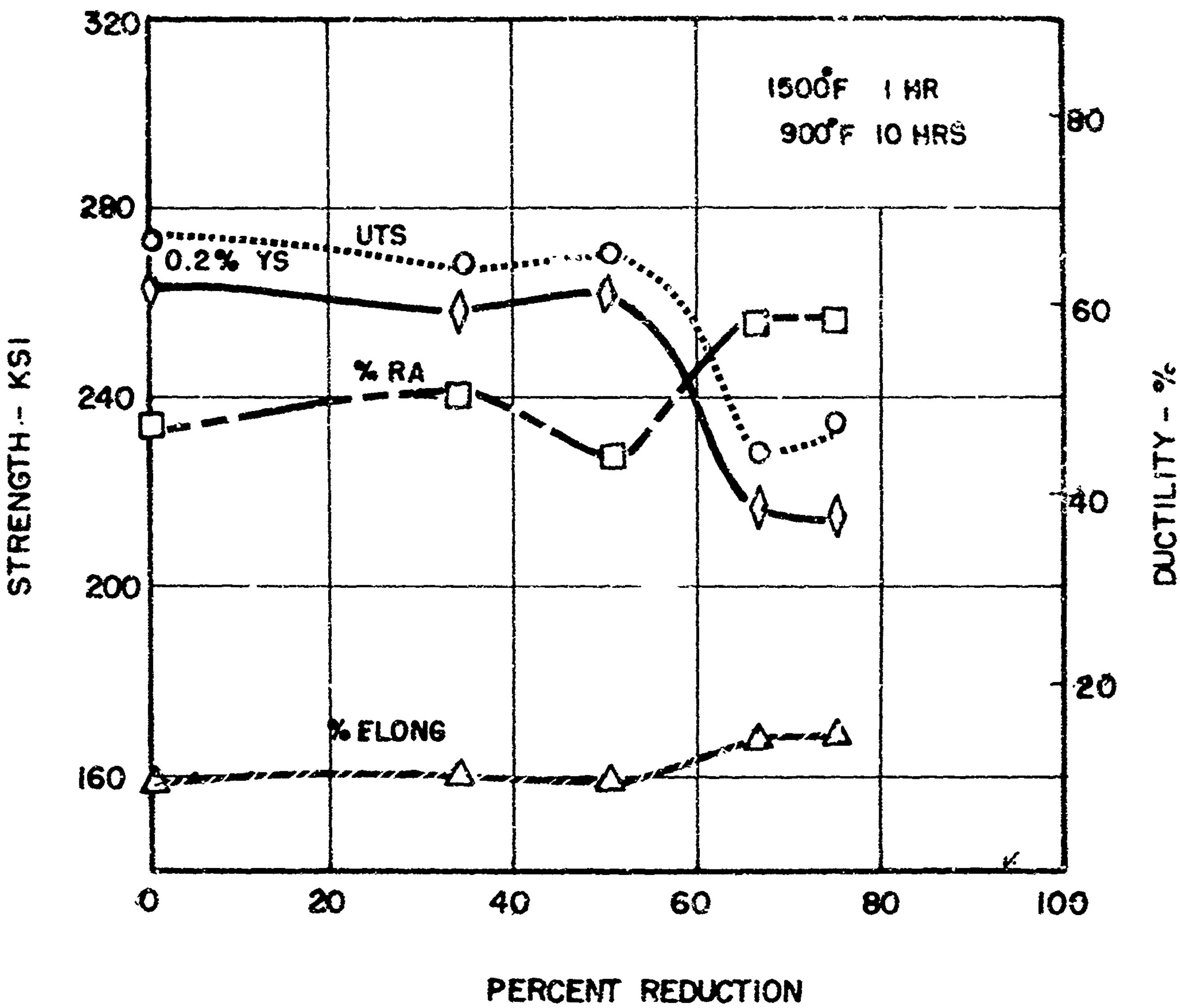
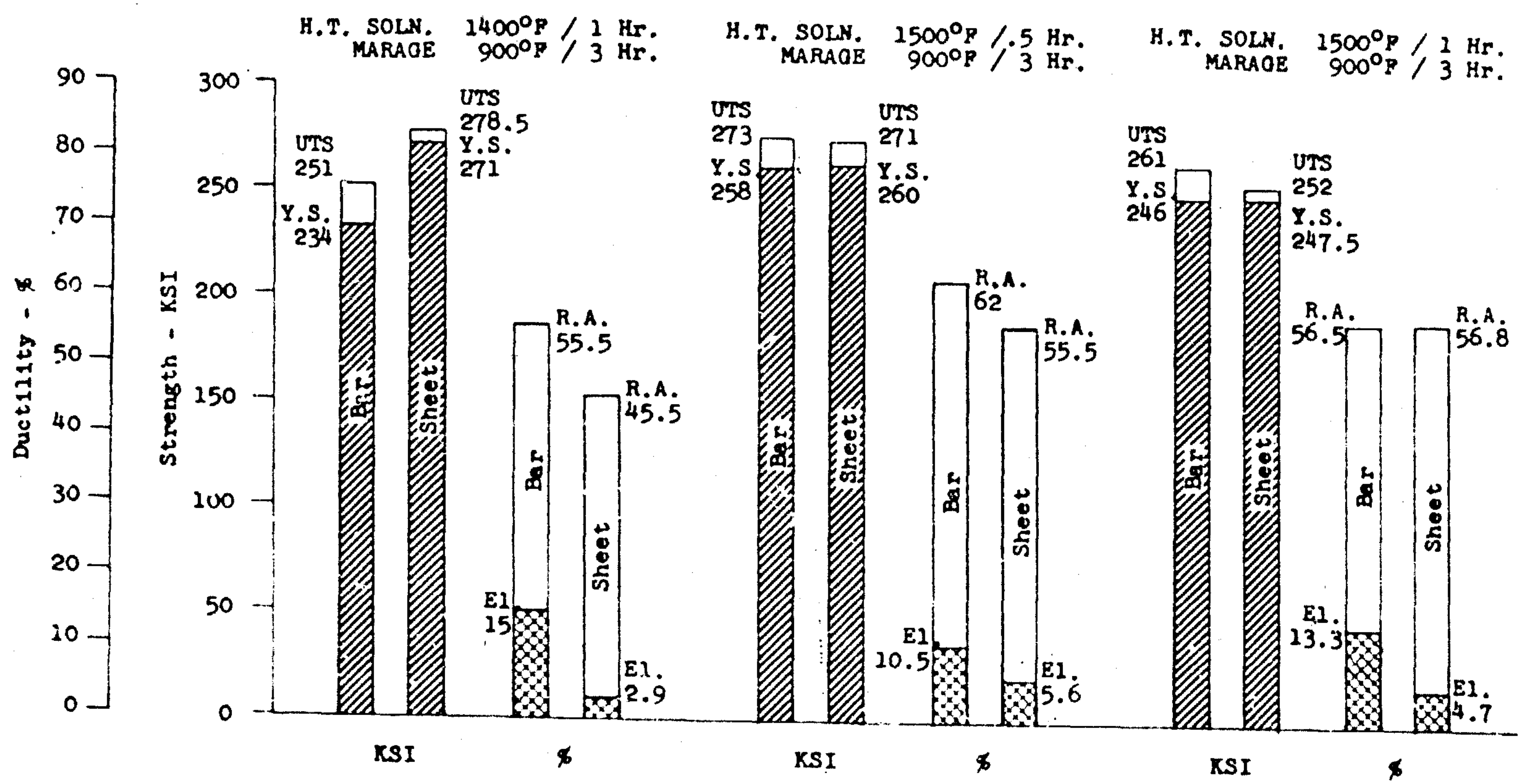


Figure 59

5342

COMPARISON OF SHEET[+] & BAR TENSILE PROPERTIES OF 18% NICKEL ALLOY (250 KSI)*



* Allegheny Heat No. 23832

+ Longitudinal Sheet Specimens

Figure 60

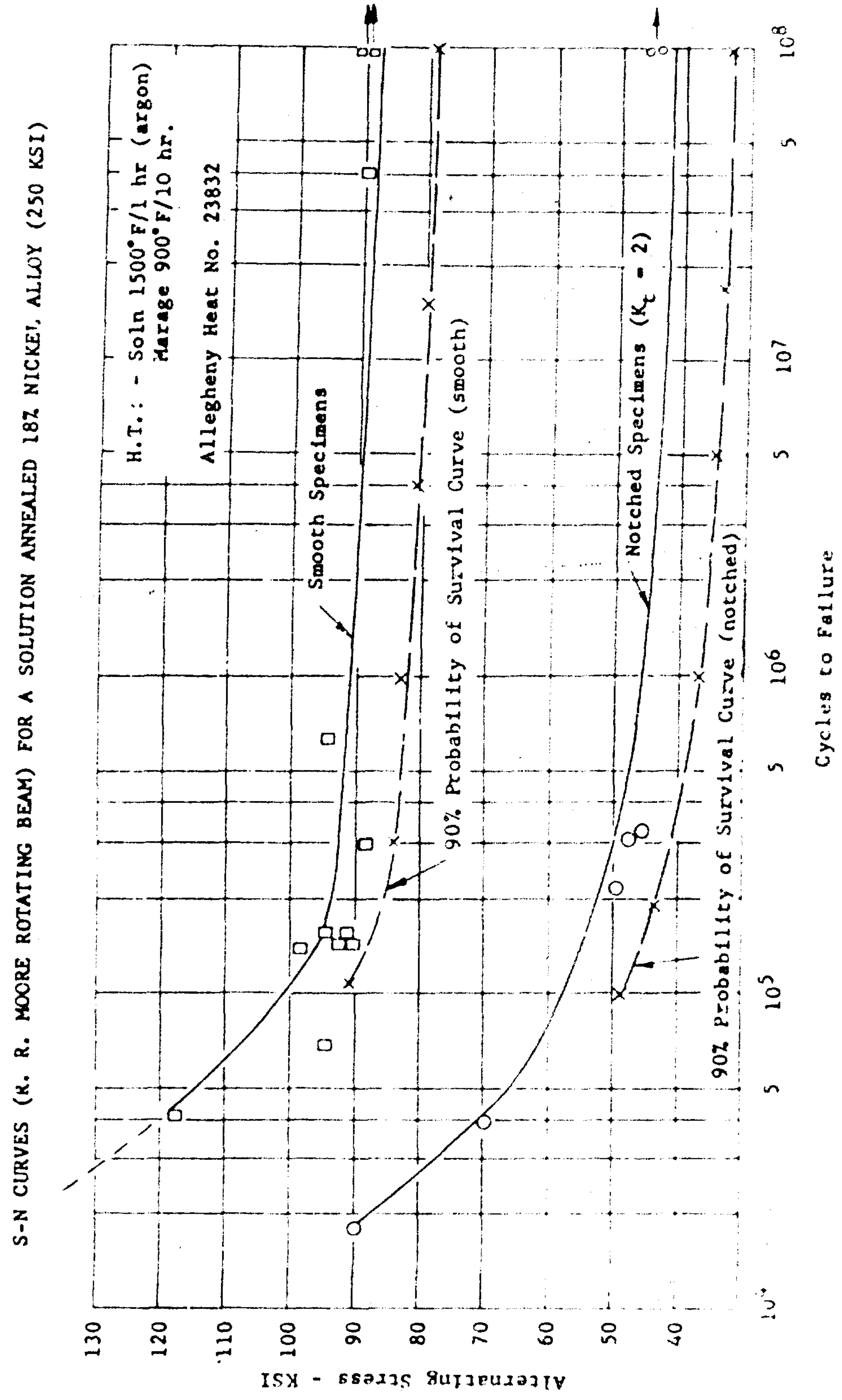
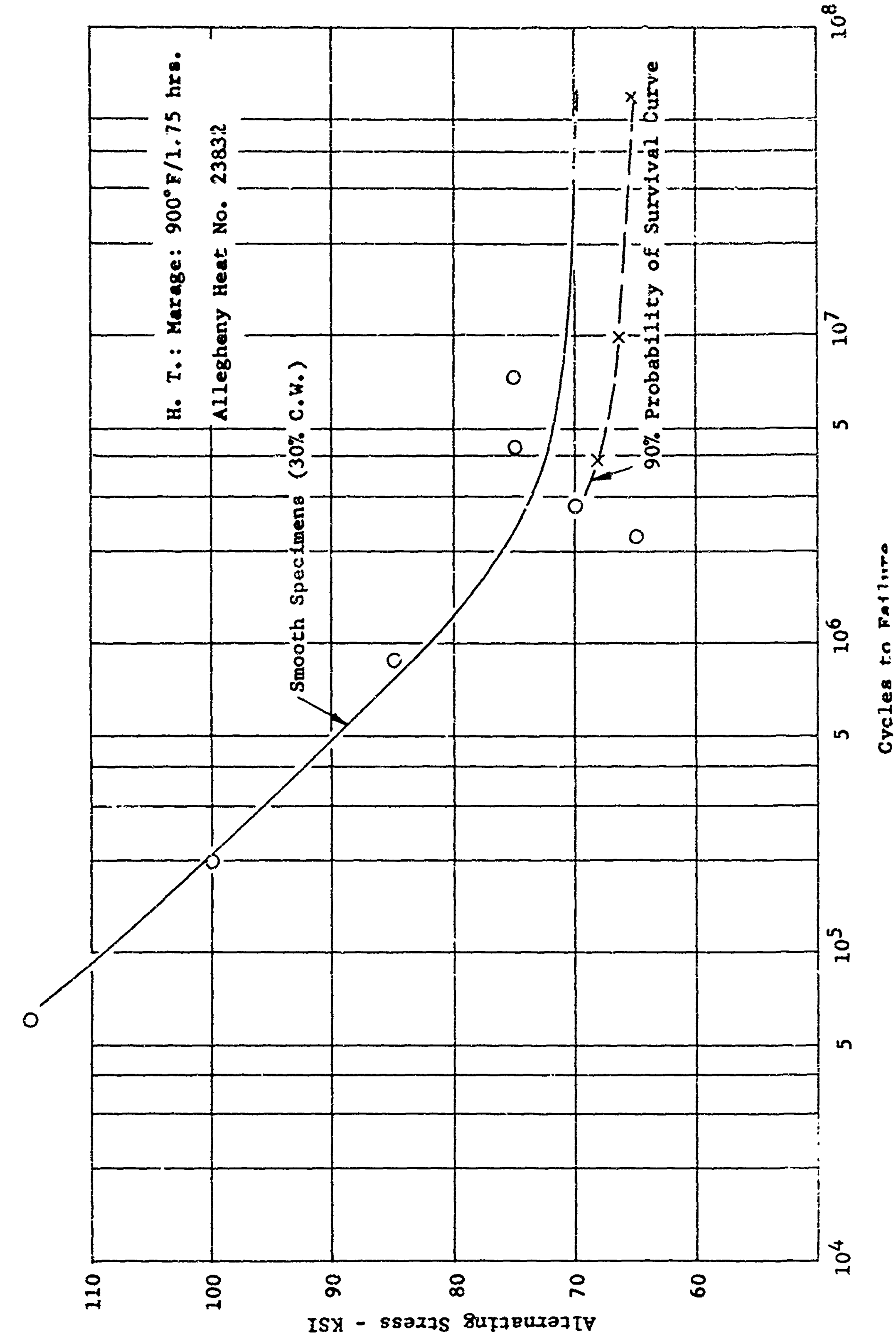

S-N CURVES (R. R. MOORE ROTATING BEAM) FOR A SOLUTION ANNEALED 18% NICKEL ALLOY (250 KSI)
H.T.: - Soln 1500°F/1 hr (argon)
Marage 900°F/10 hr.
Allegheny Heat No. 23832
Smooth Specimens
90% Probability of Survival Curve (smooth)
Notched Specimens (K_t = 2)
90% Probability of Survival Curve (notched)
Alternating Stress - KSI
130
120
110
100
90
80
70
60
50
40
Cycles to Failure
10^5
10^6
10^7
10^8
5

Figure 61



S-N CURVES (R. R. MOORE ROTATING BEAM) FOR COLD WORKED 18% NICKEL ALLOY (250 KSI)

Figure 62

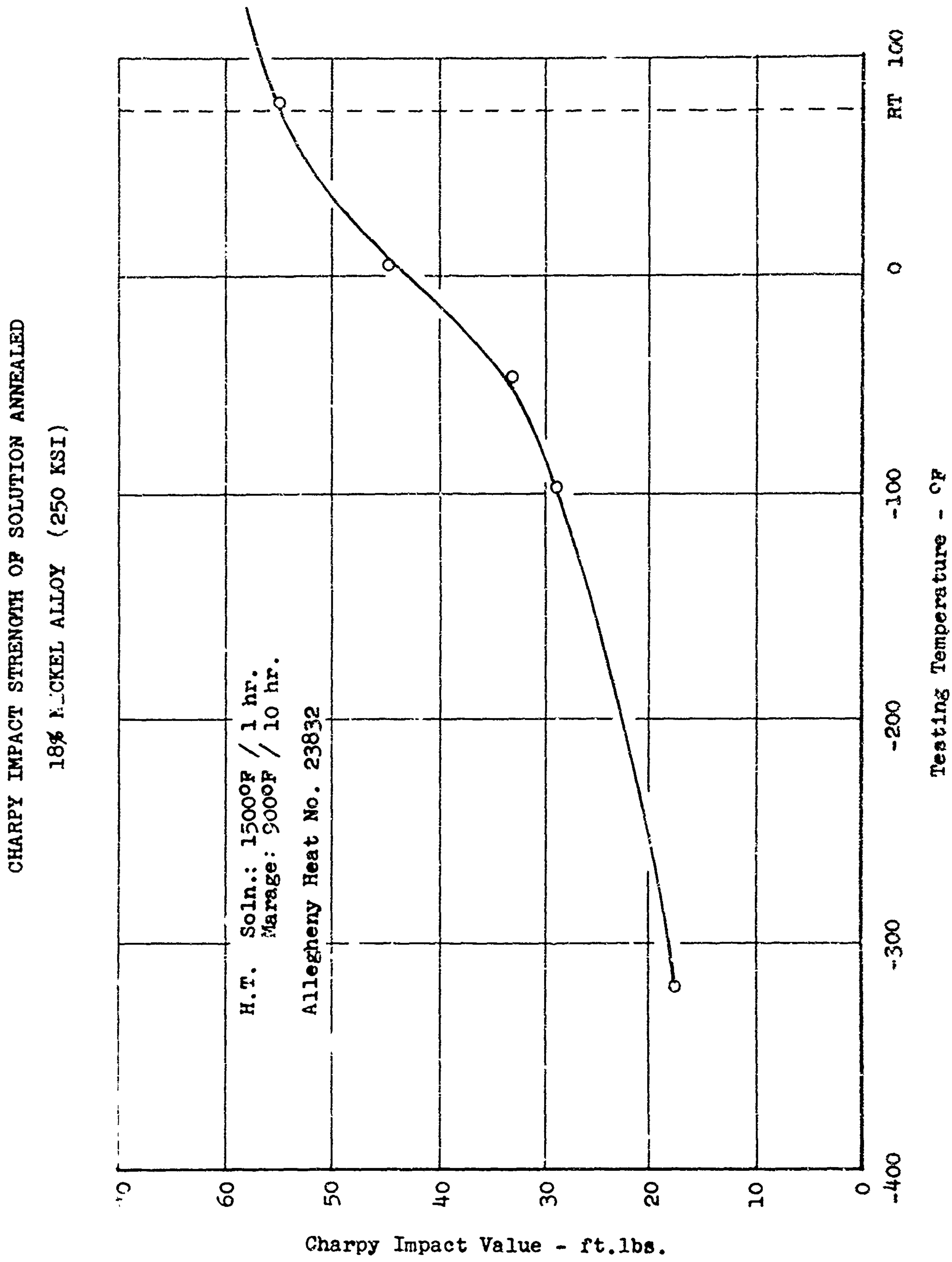

CHARPY IMPACT STRENGTH OF SOLUTION ANNEALED
18% NICKEL ALLOY (250 KSI)
H.T. Soln.: 1500°F / 1 hr.
Marage: 900°F / 10 hr.
Allegheny Heat No. 23832
Charpy Impact Value - ft.lbs.
Testing Temperature - °F
RT
100
0
-100
-200
-300
-400
70
60
50
40
30
20
10
0

Figure 63

CHARPY IMPACT STRENGTH OF COLD WORKED 18% NICKEL ALLOY (250 KSI)

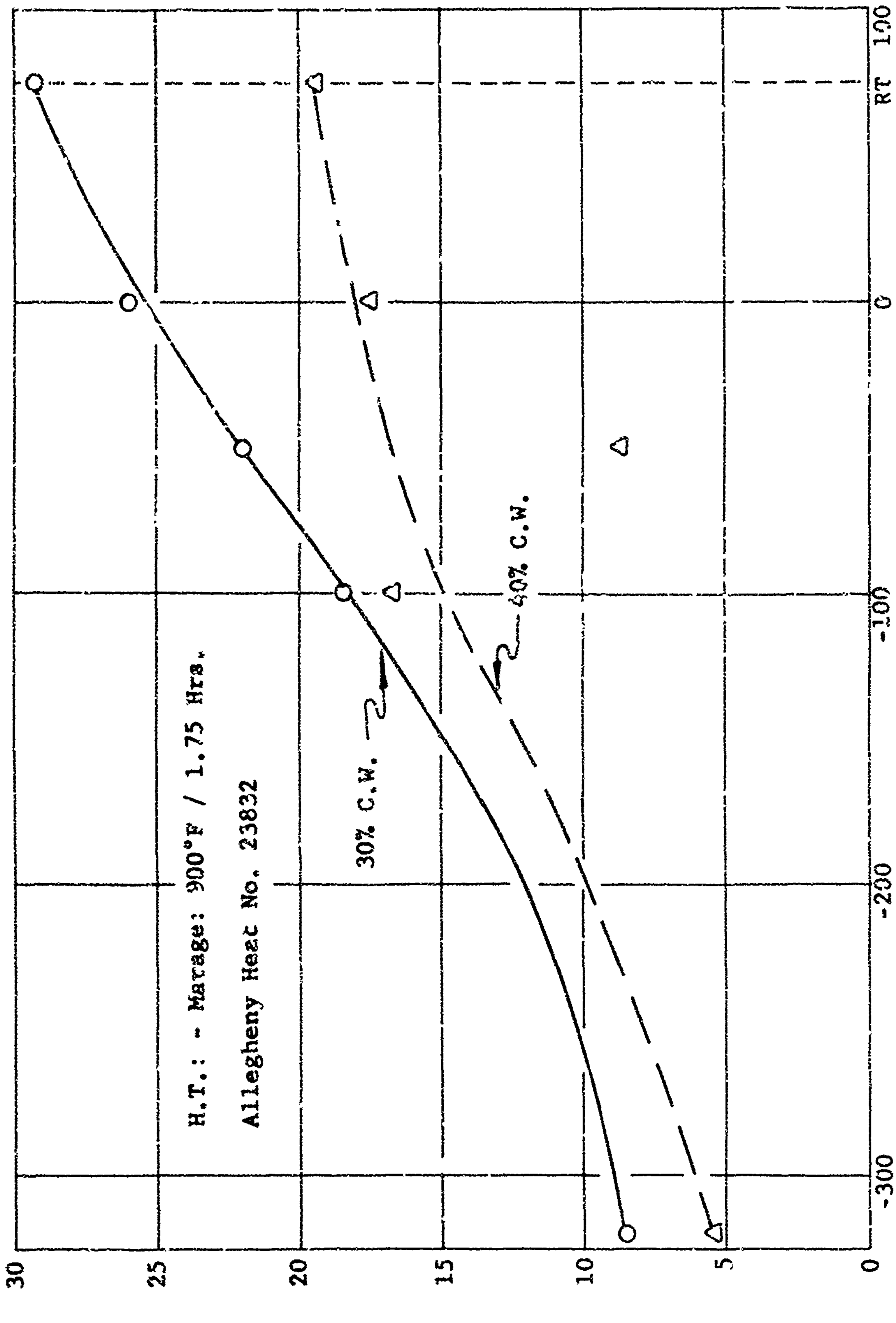


Figure 64

COMPARISON OF FRACTURE TOUGHNESS OF 18% NICKEL ALLOY (250 KSI)
IN VARIOUS CONDITIONS

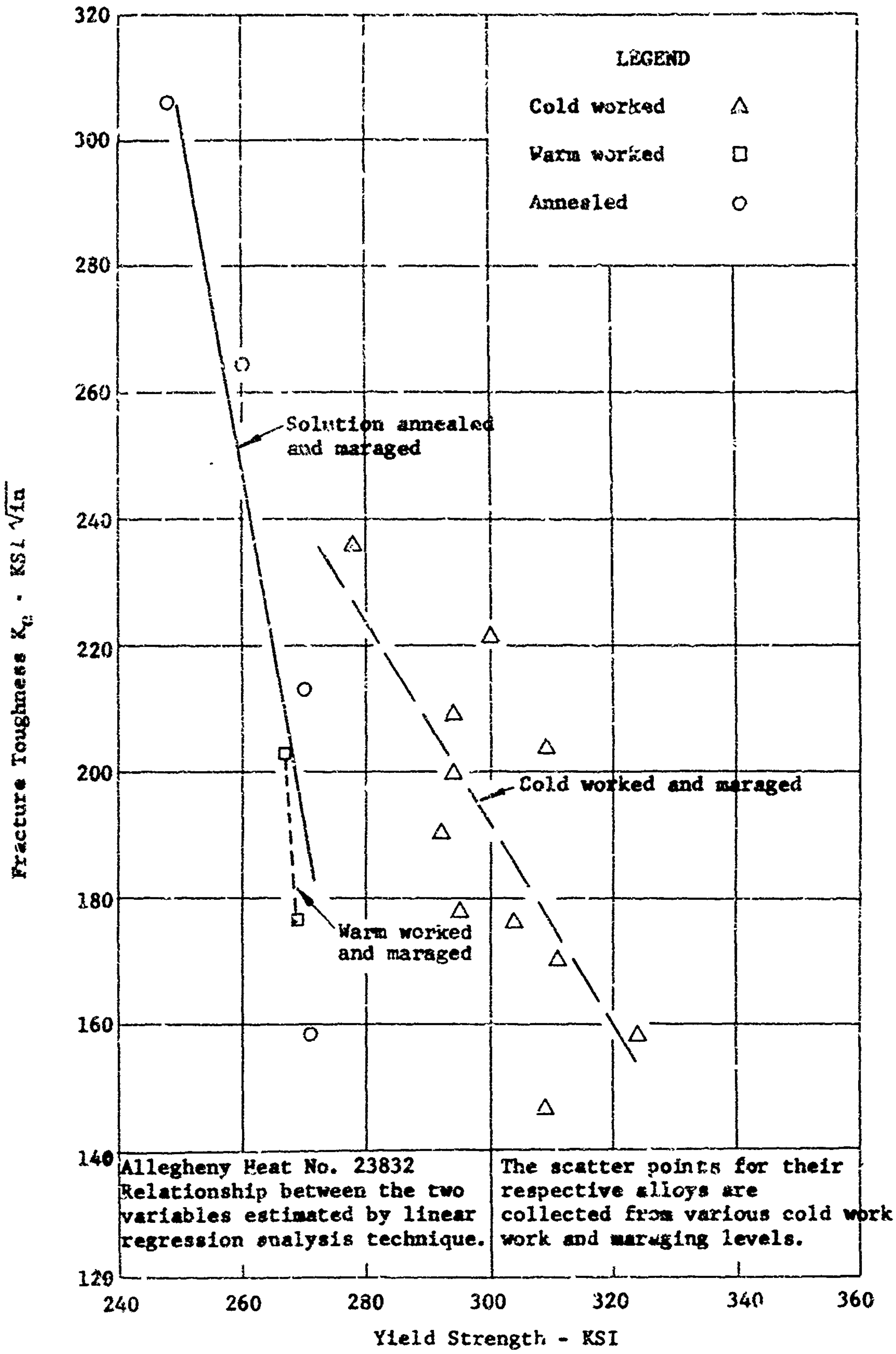
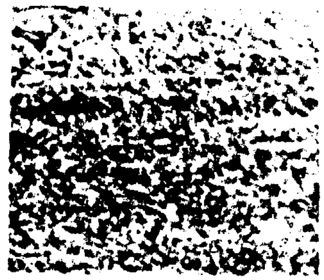


Figure 65

MICROSTRUCTURE OF SOLUTIONED 18% NICKEL (250 KSI) ALLOY

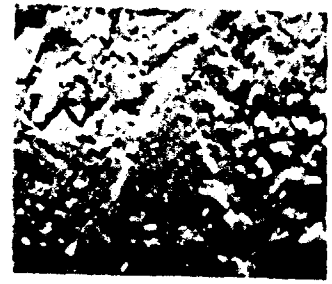
Solutioned 1400°F/1 hr.



Mag. 500 X

Etchant: Marble's + Modified Fry's

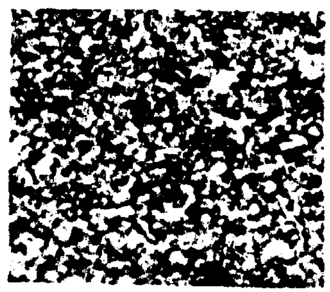
Solutioned 1400°F/1 hr.



Mag. 18000 X

Two Stage Carbon Replica

Solutioned 1500°F/1 hr.



Mag. 500 X

Etchant: Marble's + Modified Fry's

Solutioned 1500°F/1 hr.

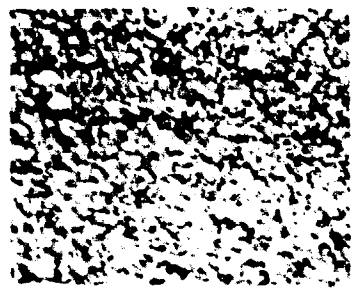
Mag. 500 X

Two Stage Carbon Replica

Figure 66

MICROSTRUCTURE OF SOLUTION AND MARAGED, AND COLD WORKED AND MARAGED 18% NICKEL (250 KSI) ALLOY

Solutioned 1500°F/1 hr., Maraged 900°F/10 hrs.



Mag. 500 X

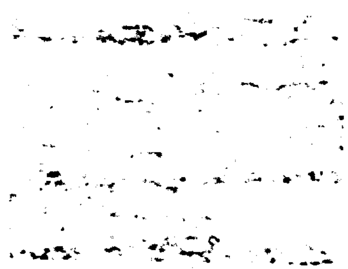
Etchant: Marble's + Modified Fry's

Solutioned 1500°F/1 hr. Marazed 900°F/10 hrs.

Mag. 18000 X

Two Stage Carbon Replica

Cold Worked 40%, Maraged 900°F/1.75 hrs.



Mag. 500 X

Etchant: Marble's + Modified Fry's

Cold Worked 40%, Maraged 900°F/1.75 hrs.

Mag. 18000 X

Two Stage Carbon Replica

Figure 67

53.5

18% NICKEL ALLOY (250 KSI) WELD HARDNESS DATA
VERTICAL TRAVERSE ALONG WELD CENTERLINE

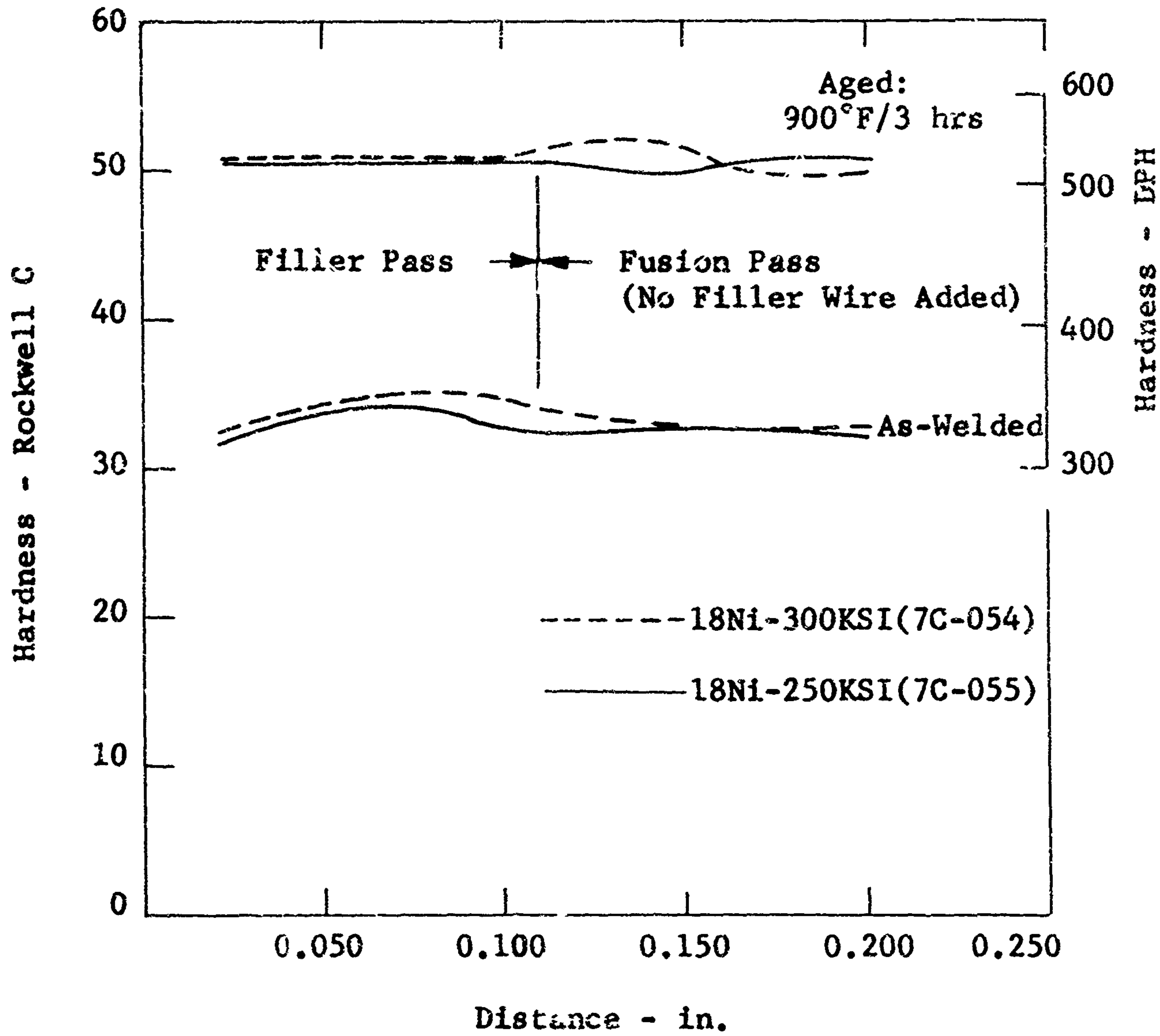
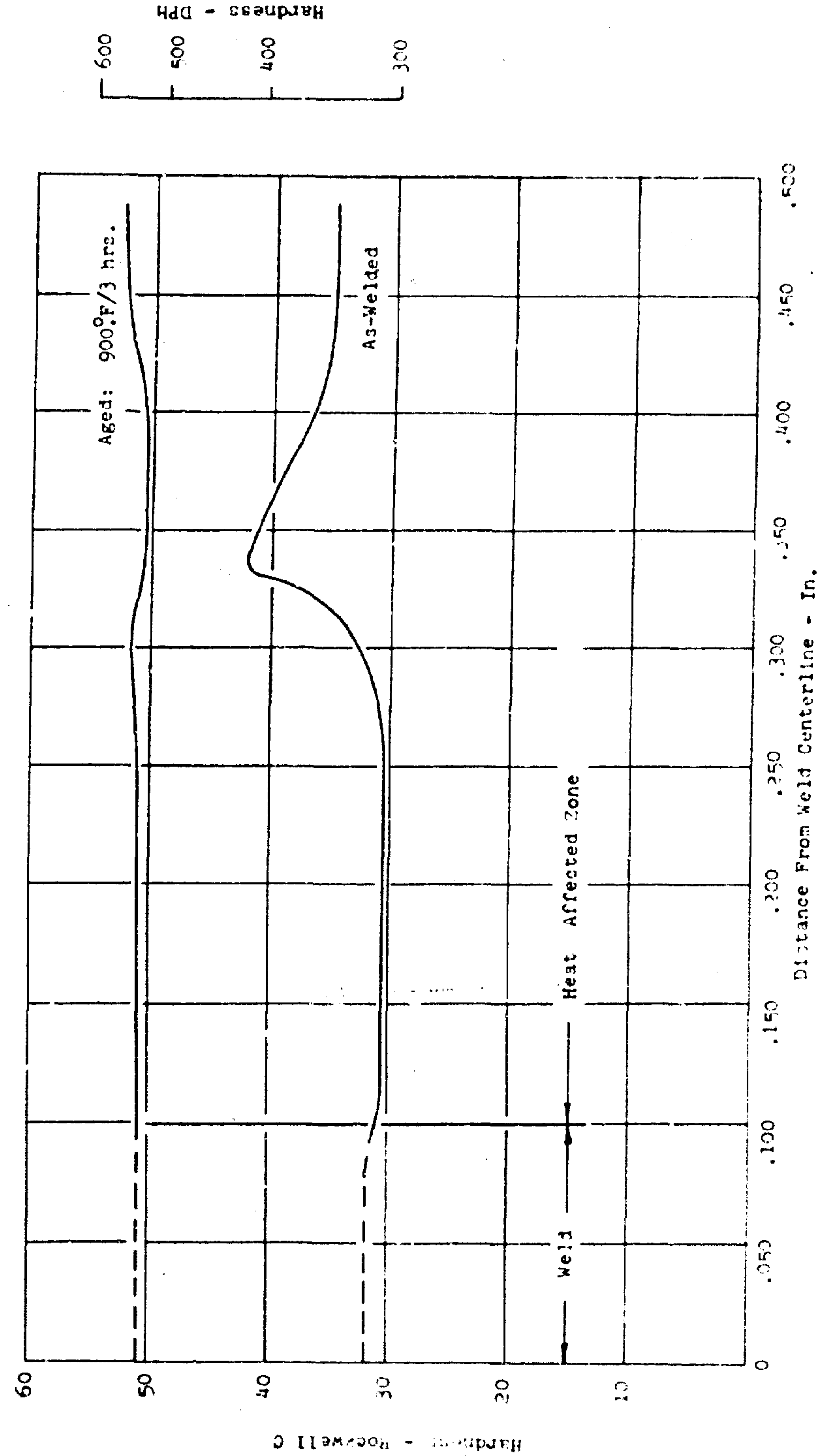


Figure 68



WELD ZONE HARDNESS SURVEY
18% NICKEL ALLOY (250 KSI) - SOLUTION HEAT TREATED

Figure 69

WELD ZONE HARDNESS SURVEY
18% NICKEL ALLOY (250 KSI) - 40% COLD WORKED

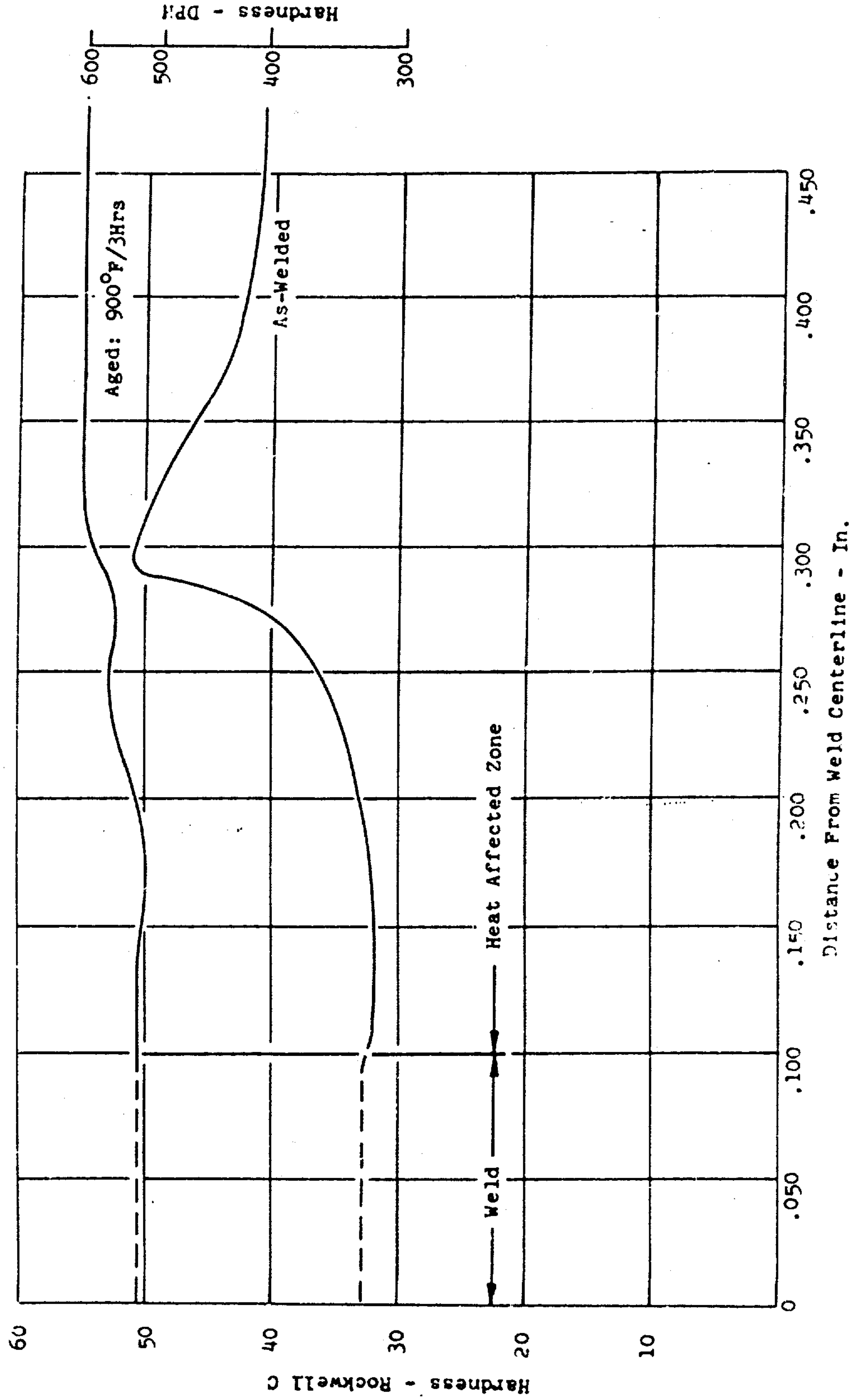


Figure 70

COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE PROPERTIES
18% NICKEL ALLOY (250) KSI) - SOLUTION HEAT TREATED SHEET

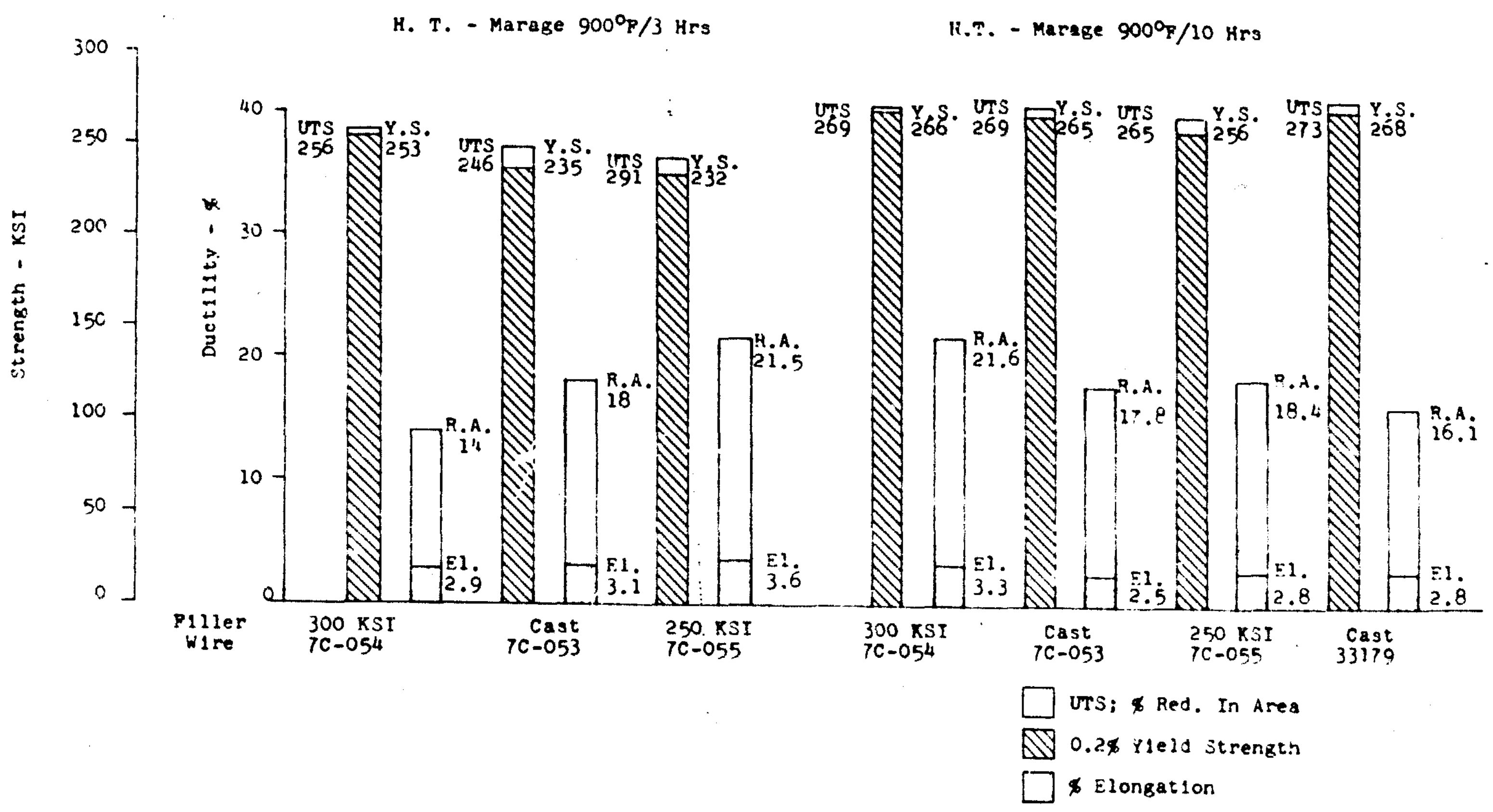


Figure 71

COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE PROPERTIES
18% NICKEL ALLOY - SOLUTION HEAT TREATED (.070" SHEET)

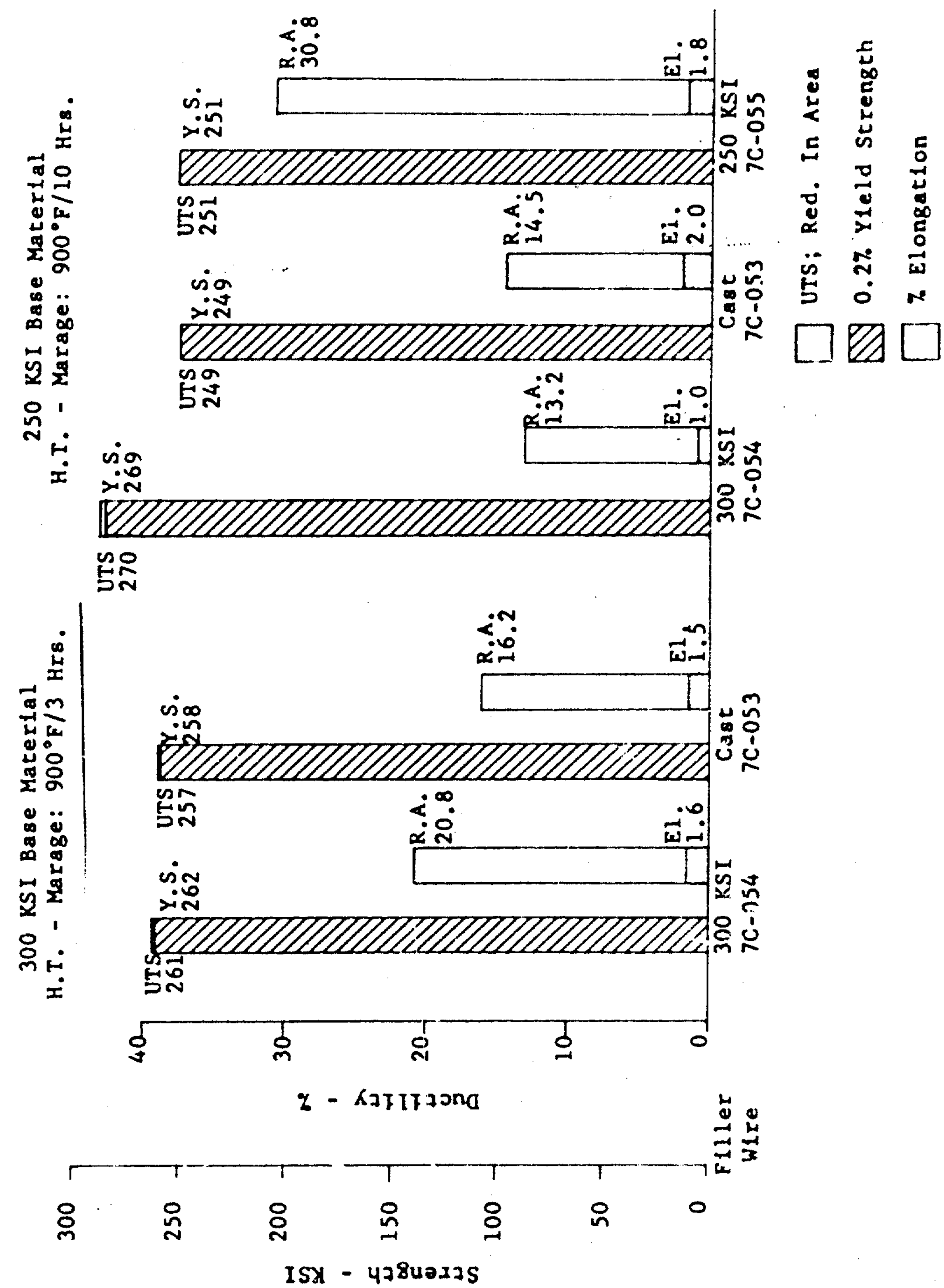
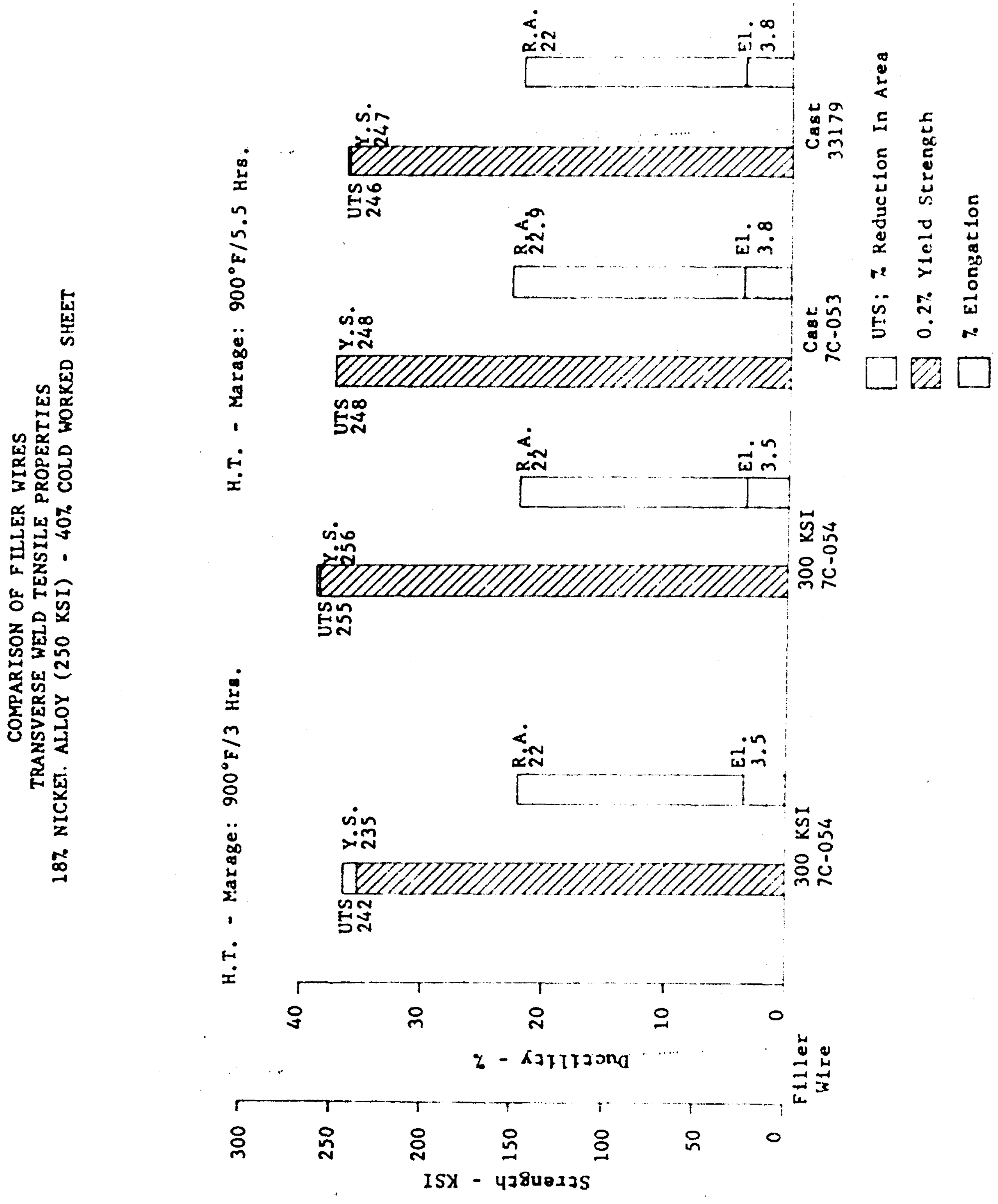


Figure 72



COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE PROPERTIES
18% NICKEL ALLOY (250 KSI) - 40% COLD WORKED SHEET
H.T. - Marage: 900°F/3 Hrs.
H.T. - Marage: 900°F/5.5 Hrs.
Strength - KSI
300
250
200
150
100
50
0
Ductility - %
40
30
20
10
0
Filler Wire
UTS 242
Y.S. 235
R.A. 22
El. 3.5
300 KSI 7C-054
UTS 255
Y.S. 256
R.A. 22
El. 3.5
300 KSI 7C-054
UTS 248
Y.S. 248
R.A. 22.9
El. 3.8
Cast 7C-053
UTS 246
Y.S. 247
R.A. 22
El. 3.8
Cast 33179
UTS; % Reduction In Area
0.2% Yield Strength
% Elongation

Figure 73

COMPARISON OF FILLER WIRES
LONGITUDINAL WELD TENSILE PROPERTIES
18% NICKEL ALLOY - SOLUTION HEAT TREATED SHEET

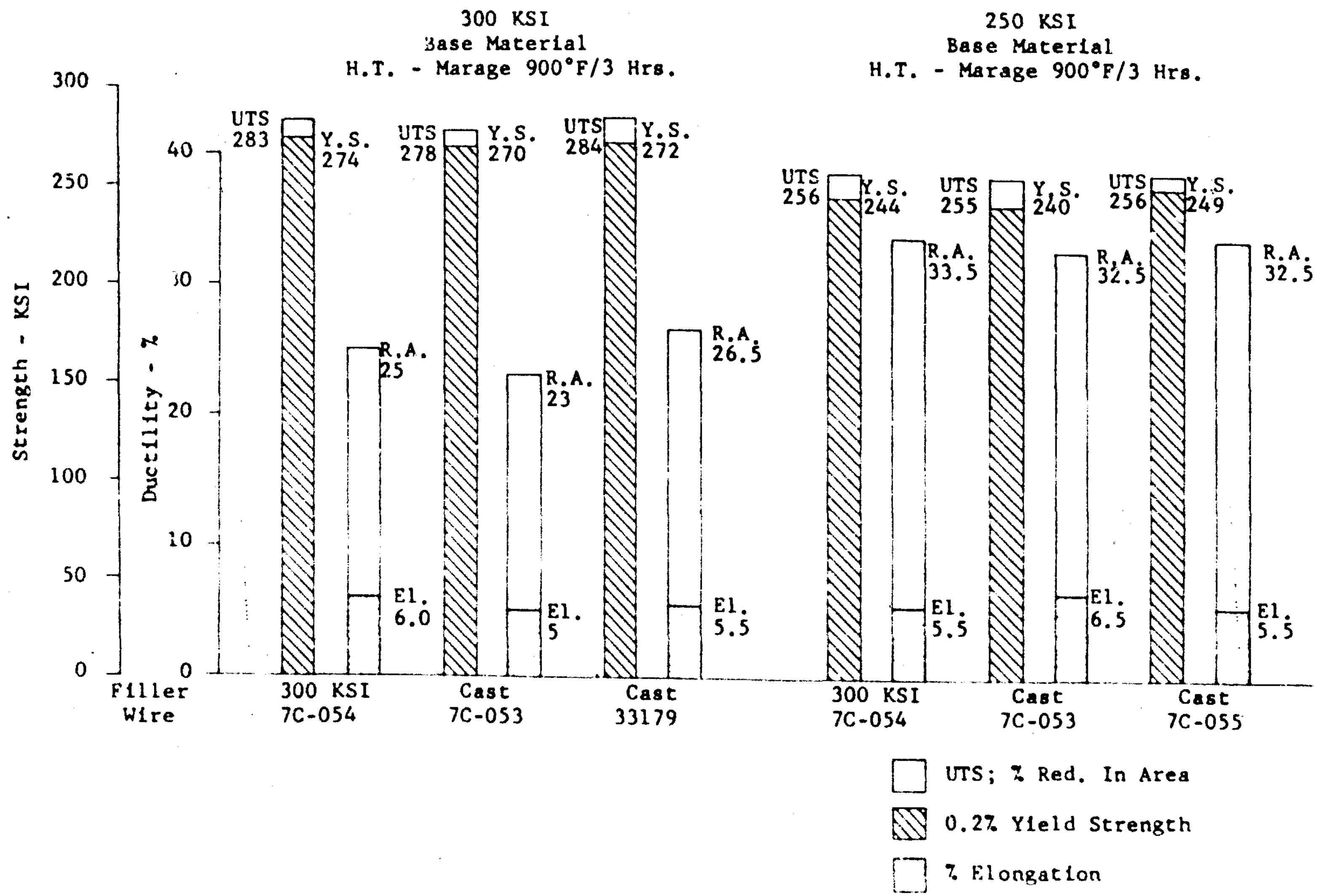


Figure 74

COMPARISON OF FILLER WIRES
TRANSVERSE WELD FRACTURE TOUGHNESS PROPERTIES
18% NICKEL ALLOY (250 KSI)-0.140" SHEET

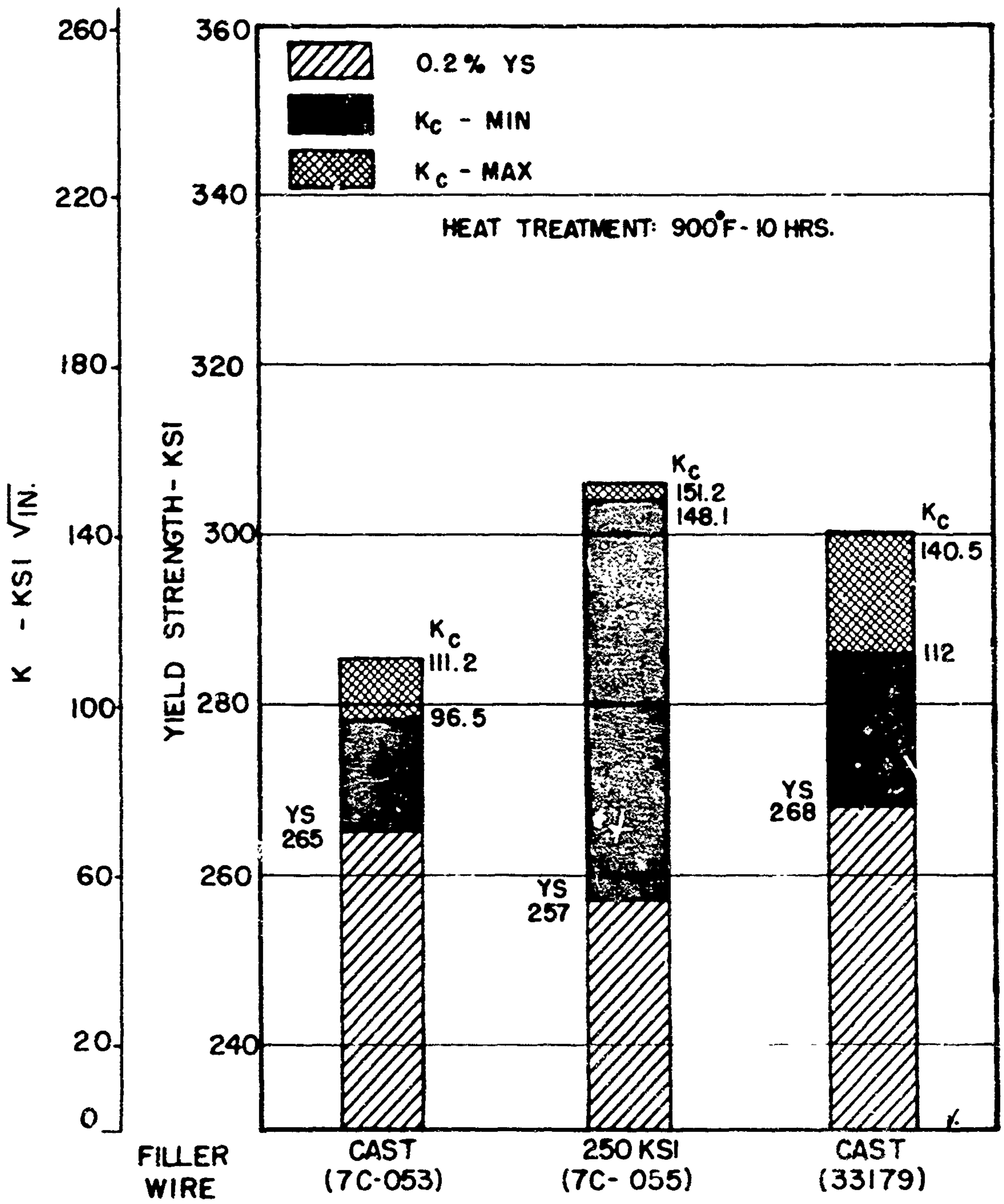


Figure 75

5374

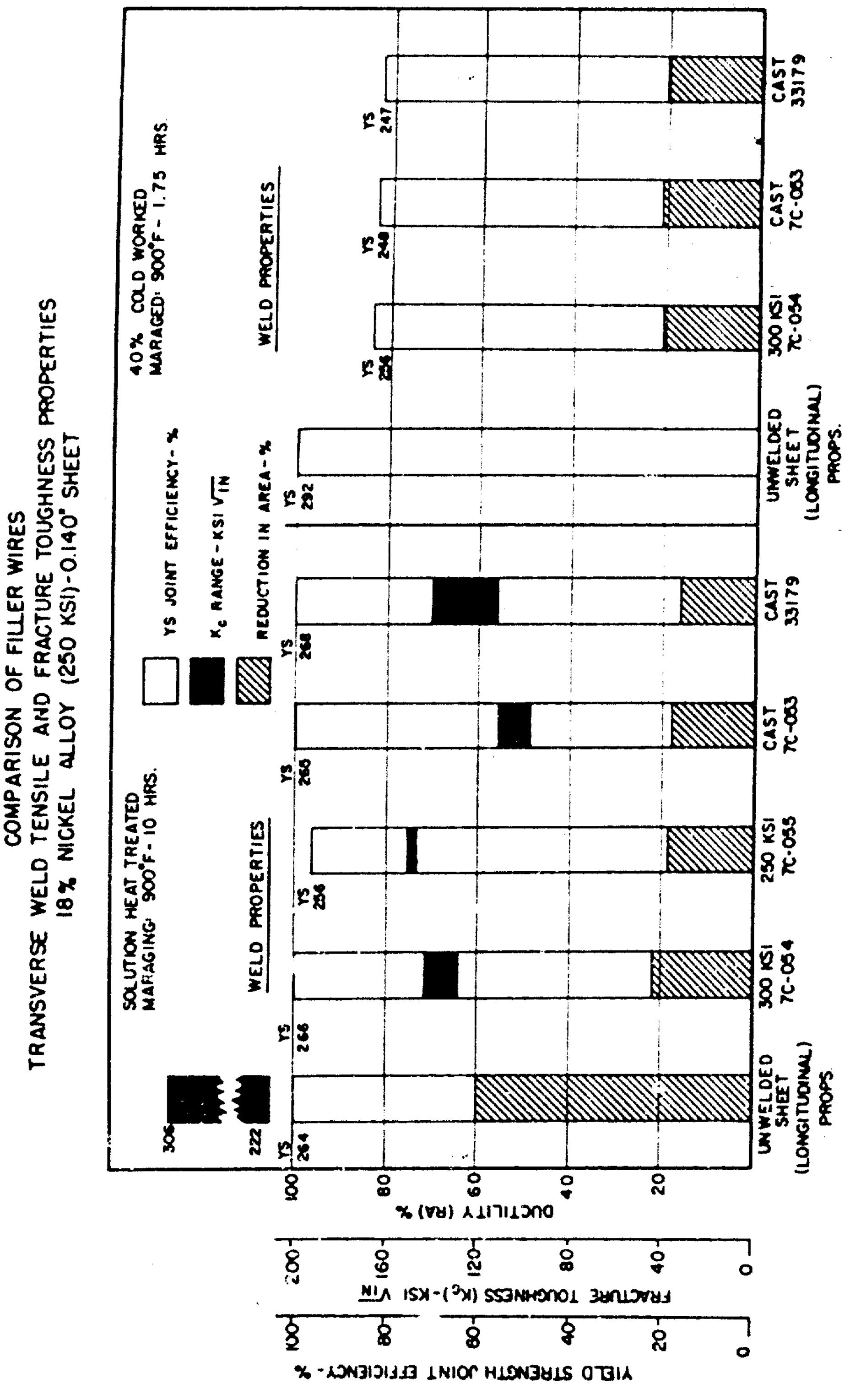

COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE AND FRACTURE TOUGHNESS PROPERTIES
18% NICKEL ALLOY (250 KSI)-0.140" SHEET
SOLUTION HEAT TREATED
MARAGING: 900°F - 10 HRS.
40% COLD WORKED
MARAGED: 900°F - 1.75 HRS
YS JOINT EFFICIENCY-%
K_c RANGE-KSI $\sqrt{IN}$
REDUCTION IN AREA-%
WELD PROPERTIES
WELD PROPERTIES
UNWELDED SHEET (LONGITUDINAL) PROPS.
300 KSI 7C-054
250 KSI 7C-055
CAST 33179
UNWELDED SHEET (LONGITUDINAL) PROPS.
300 KSI 7C-054
CAST 33179
DUCTILITY (RA) %
FRACTURE TOUGHNESS (K_c)-KSI $\sqrt{IN}$
YIELD STRENGTH JOINT EFFICIENCY-%

Figure 76

Table 14

EFFECT OF SOLUTIONING TIME AND TEMPERATURE ON THE HARDNESS OF 18% NICKEL ALLOY* (250 KSI)

Solution Temp. °F	Solution Time-Hrs.	As Quenched Hardness (R_c)	Maraged Hardness (R_c)
1400°	¼	36	51
1400°	½	35	52
1400°	1	35.8	51
1400°	2	32.5	50.5
1400°	4	32.0	51.0
1500°	¼	32.0	52.0
1500°	½	30.5	50.5
1500°	1	30.5	50.5
1500°	2	30.5	51.0
1500°	4	30.0	50.0
1600°	¼	30.5	51.5
1600°	½	30.0	50.5
1600°	1	30.0	50.0
1600°	2	29.0	49.5
1600°	4	28.5	50.0
1700°	¼	29.5	50.5
1700°	½	29.0	50.5
1700°	1	28.5	50.0
1700°	2	28.5	49.8
1700°	4	28.0	49.0
1800°	¼	29.0	49.8
1800°	½	28.0	49.8
1800°	1	29.5	49.8
1800°	2	27.5	49.0
1800°	4	27.5	49.0

* Allegheny Heat No. 23832

** Average of 6 Readings

*** All specimens maraged @ 900°F for 3 hours after solutioning

Table 14 (Cont.)
Effect of Solutioning Time and Temperature on the Hardness of 18%
Nickel Alloy (250 KSI)

Solution Temp. ^{o}F	Solution Time-Hrs.	As Quenched Hardness (R_c)	Maraged Hardness (R_c)
1900°	¼	29.0	50.0
1900°	½	29.0	48.5
1900°	1	28.0	49.0
1900°	2	28.0	50.0
1900°	4	27.5	50.0
2000°	¼	27.5	49.5
2000°	½	27.8	50.0
2000°	1	27.0	49.0
2000°	2	26.0	48.0
2000°	4	26.8	48.2
2100°	¼	26.5	49.4
2100°	½	26.5	49.0
2100°	1	27.0	49.2
2100°	2	27.0	
2100°	4	27.8	

* Allegheny Heat No. 23832
** Average of 6 Readings
*** All specimens maraged @ 900°F for 3 hours after solutioning

Table 15

EFFECT OF MARAGING PARAMETERS ON THE HARDNESS
OF SOLUTION ANNEALED 18% NICKEL ALLOY* (250 KSI)

Maraging *** Temp. °F	Maraging Time-Hrs.	Hardness** R_c
700°	¼	36.8
700°	½	38.8
700°	2	43.5
700°	5	42.0
700°	9	44.0
800°	¼	44.0
800°	½	44.5
800°	2	47.7
800°	5	48.4
800°	9	48.2
900°	¼	46.5
900°	½	48.5
900°	2	49.8
900°	5	50.4
900°	9	50.5
1000°	¼	48.6
1000°	½	49.7
1000°	2	50.0
1000°	5	49.0
1000°	9	48.8

* Allegheny Heat No. 23832

** Average of 6 Readings

*** Solution treated 1500°F/1 hr

Table 16

Effect of Solution Time and Temperature

on the

Longitudinal Tensile Properties of 18% Nickel Alloy *(250 KSI)

Solution Temp ** °F	Solution Time Hrs.	Ult. Tensile Strength KSI	0.2% Yield Strength KSI	% Elong.	% Red. in Area
1400	1	272	267	1.5	44
1400	1	288	276	4.0	46
1400	1	279	274	4.0	46
1400	1	275	266	2.0	47
[illegible]00	½	267	257	5.7	60
1500	1	255	243	5.0	57
1500	½	275	263	5.5	51
1500	1	258	247	5.0	58
1500	1	257	249	3.9	55
1500	1	258	251	5.0	57
1500	1.5	268	253	6.0	56
1500	1.5	258	248	7.0	52
1500	2	263	251	6.0	45
1500	2	260	251	6.0	45
1600	1	258	247	5.0	54
1600	1	255	243	5.0	54
1600	1	255	248	6.0	47
1600	1	257	247	4.0	47
1700	1	249	235	7.0	50
1700	1	251	236	6.0	44
1700	1	248	238	6.0	38
1700	1	247	231	6.0	55

** All specimens solution annealed (argon atmosphere) under the above conditions, air quenched and then, maraged at 900°F for 3 hours.

* Allegheny Ludlum Heat No. 23832.

Table 17

Effect of Solution Time and Temperature

on the

Transverse Tensile Properties of 18% Nickel Alloy *(250 KSI)

Solution Temp ** °F	Solution Time Hrs.	Ult. Tensile Strength KSI	0.2% Yield Strength KSI	% Elong.	% Red. in Area
1500	½	272	264	4.0	55
1500	½	273	267	6.0	52
1500	1.5	267	261	7.0	56
1500	1.5	269	262	4.9	53
1500	2	283	273	6.0	37
1500	2	260	247	6.0	44

** All specimens solution annealed (argon atmosphere) under the above conditions, air quenched and then, maraged at 900°F for 3 hours.

* Allegheny Ludlum Heat No. 23832.

Table 18

EFFECT OF SOLUTION TREATMENT ON FRACTURE TOUGHNESS OF 18% NI ALLOY* (250 KSI)

Orientation of Specimen Axis to Rolling Direction	Solution** Temp. °F	Solution Time Hrs.	0.2% Yield Str. KSI	Net Fracture Stress(1) KSI	Notch Strength KSI (2)	β (3)	Critical Crack Index(4)	Kc (5) $KSI\sqrt{In}$	Gc (6) + In-lbs/in^2
Parallel	1400	1	271	211	164	3.07	0.12	163	1030
			271	199	161	2.74	0.10	154	919
Normal	1400	1	278	161	125	1.58	0.06	122	577
			278	152	122	1.40	0.05	115	513
Parallel	1500	½	260	275	222	7.53	0.28	245	2327
			260	291	226	10.38	0.38	284	3126
Normal	1500	½	266	238	203	4.42	0.17	196	1489
			266	262	220	6.02	0.23	226	1980
Parallel	1500	1	250		250***			222	1910****
			250		236***			227	2000****
			248		235***				
			248	298	237	12.69	0.45	306	3625
Normal	1500	1	263	328	269	11.50	0.45	314	3822
			263		228***				
			256	263	224	6.79	0.26	231	2068

* Allegheny Ludlum Heat No. 23832
** All specimens maraged at 900°F for 3 hrs.
*** Specimens tore through pinhole
**** Gc minimum calculated on basis of compliance gage data
\+ Centrally notched, fatigue cracked specimens

TABLE 19

EFFECT OF MARAGING TREATMENT ON THE LONGITUDINAL TENSILE PROPERTIES
SOL . ANNEALED 18% NICKEL ALLOY* (250 KSI)

Marage Temp °F	Marage Time Hrs.	Ult. Ten. Str. KSI	0.2% Yield Str. KSI	% Elong.	% R.A.
900	1	240	230	6	52
"	1	242	235	7	51
"	3	264	254	6	50
"	3	267	252	6	40
"	10	275	263	6	57
"	10	274	264	7	62
850	1	222	212	7	53
"	1	225	210	7	53
"	3	241	232	7	50
"	3	247	234	6	47
"	10	273	261	6	52
"	10	268	259	6	46
950	1	253	245	7	56
"	1	256	249	6	54
"	3	262	248	7	43
"	3	267	255	6	55
"	10	261	254	6	46
"	10	266	245	7	50

* All specimens solution annealed at 1500°F for 1 hour, air quenched, and, then, maraged under the above conditions

TABLE 20

EFFECT OF MARAGING TREATMENT ON THE TRANSVERSE TENSILE PROPERTIES OF SOL. ANNEALED 18% NICKEL ALLOY* (250 KSI)

Marage Temp °F	Marage Time Hrs.	Ult. Ten. Str. KSI	0.2% Yield Str. KSI	% Elong.	% R.A.
900	1	251	238	6	43
"	1	250	243	5	54
"	3	271	266	5	42
"	3	264	257	5	51
850	10	280	266	4	45
"	10	272	261	5	48
"	1	231	218	7	48
"	1	234	230	7	47
"	3	250	235	6	48
"	3	248	238	6	49
900	10	281	271	5	52
"	10	281	271	5	44
950	1	264	251	5	41
"	1	260	252	6	45
"	3	271	257	6	43
"	3	273	258	6	42
"	10	274	261	6	42
"	10	270	267	6	45

* All specimens solution annealed at 1500°F for 1 hour, air quenched and, then, maraged under the above conditions

Table 21

EFFECT OF MARAGING TREATMENT ON FRACTURE TOUGHNESS OF SOLUTION TREATED 18% NICKEL ALLOY* (250 KSI)

Orientation of Specimen Axis to Rolling Direction	Maraging** Temp. °F	Maraging Time Hrs.	0.2% Yield Str. KSI	Net Fracture Stress KSI	Notch Str. KSI	β (3)	Critical Crack Index (4)	K_c (5) KSI In	G_c (6) in.lb/in^2
Parallel	900	1	240		232***				
Parallel			240		210***				
Normal			240		234***				
Normal			240		238***				
Parallel		3	260		221***				
Parallel			260		240***				
Normal			260	254	211	5.37	0.21	212	1750
Normal			260	266	244	6.67	0.26	234	2110
Parallel		10	270	248	232	5.27	0.19	210	1700
Parallel			270	256	236	5.50	0.20	216	1820
Normal			270	218	188	3.27	0.14	176	1210
Normal			270	219	187	3.45	0.13	175	1210

* Allegheny Ludlum Heat No. 23832
** All Specimens Solution Treated At 1500°F For 1 Hour
Centrally Notched, Fatigue Cracked Specimens
*** Specimens Tore Through Pin Hole

TABLE 22

LONGITUDINAL TENSILE PROPERTIES OF COLD WORKED 18% NICKEL ALLOY (250 KSI)

% Reduction	Marage Temp °F	Marage Time Hours	Ult. Tens. Str. KSI	0.2% Yield Str. KSI	% Elong.	% R.A.
20	850	1	246	244	4.9	46
"	"	1	247	247	4.5	41
"	900	1	263	263	4.3	52
"	"	1	267	266	3.6	54
"	850	3	268	268	4.6	45
"	"	3	259	257	4.3	50
"	900	3	275	273	4.3	56
"	"	3	284	282	4.8	52
"	850	10	292	289	4.6	49
"	"	10	292	287	4.9	55
"	900	10	288	283	3.5	47
"	"	10	280	274	4.8	48
30	850	1	278	277	3.7	50
"	"	1	277	277	4.5	53
"	900	1	291	291	4.3	54
"	"	1	293	291	4.4	47
"	850	3	297	295	4.2	37
"	"	3	289	288	4.2	53
"	900	3	294	290	4.0	49
"	"	3	300	297	4.7	54
"	850	10	306	302	4.1	42
"	"	10	306	299	4.4	47
"	900	10	294	289	5.0	49
"	"	10	293	290	4.9	54
40	850	1	293	290	2.5	43
"	"	1	294	294	4.3	47
"	900	1	308	306	4.0	49
"	"	1	284	284	1.9	47
"	850	3	295	295	4.2	47
"	"	3	309	302	4.2	49
"	900	3	307	303	3.3	47
"	"	3	317	315	4.4	57
"	850	10	319	319	3.0	48
"	"	10	327	326	3.4	43
"	900	10	305	300	4.1	51
"	"	10	307	297	4.5	53

TABLE 22 (Continued)

% Reduction	Marage Temp °F	Marage Time Hours	Ult. Tens. Str. KSI	0.2% Yield Str. kSI	% Elong.	% R.A.
40	850	1	287	284	4.3	46
"	"	1	282	280	4.6	52
"	900	1	300	298	3.9	49
"	"	1	295	292	4.0	48
"	850	3	299	299	3.4	43
"	"	3	298	297	4.1	50
"	900	3	293	289	4.3	52
"	"	3	300	298	4.5	56
"	850	10	309	309	4.7	53
"	"	10	312	308	4.6	52
"	900	10	302	295	3.5	53
"	"	10	300	295	4.8	52
50	850	1	297	293	4.0	43
"	"	1	298	296	4.9	47
"	900	1	312	309	4.3	50
"	"	1	308	305	4.3	51
"	850	3	316	314	4.3	45
"	"	3	310	309	4.2	52
"	900	3	313	309	4.2	54
"	"	3	315	313	4.4	45
"	850	10	324	324	4.0	52
"	"	10	FAILED AT PINHOLE			
"	900	10	311	305	4.4	47
"	"	10	311	303	4.3	53

TABLE 23

TRANSVERSE TENSILE PROPERTIES OF COLD WORKED 18% NICKEL ALLOY (250 KSI)

% Reduction	Marage Temp °F	Marage Time Hours	Ult. Tens. Str. KSI	0.2% Yield Str. KSI	% Elong.	% R.A.
20	850	1	264	262	4.4	54
"	"	1	259	257	4.7	51
"	900	1	285	285	3.2	46
"	"	1	274	274	3.1	45
"	850	3	289	289	2.8	49
"	"	3	285	281	4.5	48
"	900	3	291	287	4.1	47
"	"	3				
"	850	10	301	297	4.2	41
"	"	10	305	304	2.8	43
"	900	10	301	295	4.5	42
"	"	10	303	302	3.9	41
30	850	1	283	282	4.2	44
"	"	1	291	289	3.4	45
"	900	1	306	301	4.0	44
"	"	1	306	302	3.2	49
"	850	3	272	272	1.2	41
"	"	3	302	301	3.8	39
"	900	3	317	310	4.1	42
"	"	3	305	302	4.1	43
"	850	10	324	319	3.8	44
"	"	10	321	316	3.8	42
"	900	10	316	308	3.8	47
"	"	10	315	306	4.0	44
40	850	1	294	294	4.0	35
"	"	1	286	283	3.7	43
"	900	1	306	301	3.6	43
"	"	1	304	302	3.4	44
"	850	3	303	303	3.8	44
"	"	3	310	306	4.0	42
"	900	3	316	311	2.6	39
"	"	3	313	311	3.3	40
"	850	10	327	320	3.8	38
"	"	10	329	324	3.8	36
"	900	10	315	308	4.3	38
"	"	10	314	309	4.0	41

TABLE 23 (Continued)

% Reduction	Marage Temp °F	Marage Time Hours	Ult. Tens. Str. KSI	0.2% Yield Str. KSI	% Elong.	% R.A.
50	850	1	318	311	4.1	44
"	"	1	319	316	2.8	35
"	900	1	330	327	2.7	40
"	"	1	333	330	3.6	32
"	850	3	FAILED AT PINHOLE			-
"	"	3	322	318	3.9	37
"	900	3	331	327	3.3	38
"	"	3	327	324	4.0	45
"	850	10	FAILED AT PINHOLE			-
"	"	10	FAILED AT PINHOLE			-
"	900	10	323	318	3.6	35
"	"	10	323	318	2.7	39
70	850	1	301	301	2.4	37
"	"	1	309	309	1.3	23
"	900	1	322	322	2.5	17
"	"	1	320	318	2.5	18
"	850	3	FAILED AT PINHOLE			-
"	"	3	FAILED AT PINHOLE			-
"	900	3	323	320	2.0	6
"	"	3	327	325	2.0	12
"	850	10	FAILED AT PINHOLE			-
"	"	10	FAILED AT PINHOLE			-
"	900	10	326	314	3.1	18
"	"	10	317	315	2.2	18

TABLE 24

EFFECT OF COLD WORK & MARAGING PARAMETERS ON FRACTURE TOUGHNESS OF 18% NICKEL ALLOY* (250 KSI)

% Reduction	Orientation of Specimen Axis to Rolling Direction	Maraging Temp °F	Maraging Time Hrs	0.2% Yield Str. KSI	Net Fracture Stress(1) KSI	Notch Strength(2) KSI	$\bar{\rho}$ (3)	Critical Crack Index(4) in	Kc(5) KSI $\sqrt{in}$	Gc(6) in-lb/in^2
20	Parallel	900	3	278	276	236	6.06	0.23	236	2150
	Normal			287	206	167	2.48	0.10	158	970
30	Parallel	850	10	300	289	255	5.60	0.21	246	2340
				300	248	209	3.88	0.14	197	1500
	Normal			317	170	132	1.27	0.05	124	600
				317	186	145	1.61	0.06	139	750
	Parallel	900	3	294	250	210	3.85	0.15	200	1550
	Normal			305	178	139	1.56	0.06	132	675
	Parallel		5.5	292	221	187	2.96	0.11	174	1173
				292	252	223	4.18	0.16	207	1661
	Normal			306	162	129	1.26	0.05	119	549
				306	236	136	2.10	0.08	154	910
40	Parallel	850	10	309	262	216	3.87	0.15	209	1700
				309	248	212	3.52	0.13	199	1530
	Normal			322	158	118	1.06	0.04	114	505
				322	166	125	1.19	0.05	121	567
	Parallel	900	3	294	232	191	3.35	0.13	186	1335
				294	274	234	5.26	0.20	232	2085
			10	295	228	200	3.28	0.12	181	1260
				295	221	194	2.96	0.11	175	1190
	Normal	900	3	311	136	113	0.88	0.03	101	392
				311	139	116	0.88	0.03	103	414
			10	309	171	116	1.32	0.05	122	577
				309	164	113	1.22	0.05	118	535
50	Parallel	850	10	324	211	179	4.08	0.16	161	1005
				324	206	176	1.92	0.07	156	940
	Normal			323	136	98	0.73	0.03	96	360
				323	124	98	0.63	0.03	90	314
	Parallel	900	3	311	203	175	2.11	0.08	157	944
				311	235	200	2.85	0.11	184	1310
			10	304	216	173	2.47	0.10	166	1070
				304	237	196	3.16	0.12	187	1360
	Normal		3	326	127	102	0.67	0.03	94	338
				326	118	95	0.58	0.02	87	293
			10	318	128	102	0.69	0.03	92	325
				318	120	96	0.61	0.02	86	290
70	Parallel	900	3	309	196	159	1.99	0.08	150	873
				309	189	155	1.77	0.07	143	790
	Normal			323	123	100	0.63	0.02	90	314
				323	144	108	0.76	0.03	99	370

TABLE 25

LONGITUDINAL TENSILE PROPERTIES OF WARM WORKED 18% NICKEL ALLOY (250 KSI)

Warm Work Temp. °F	Marage Temp. °F	Marage Time Hours	Ult. Tens. Str. KSI	0.2% Yield Str. KSI	% Elong	% R.A.
1200	850	1	175	171	15	49
"	"	1	182	176	18	50
"	900	1	171	160	19	33
"	"	1	183	168	17	44
"	850	3	186	174	17	34
"	"	3	177	171	16	43
"	900	3	181	171	17	68
"	"	3	180	178	17	62
"	850	10	177	173	18	54
"	"	10	187	189	12	53
"	900	10	182	174	16	63
"	"	10	178	170	16	51
1400	850	1	233	228	6	44
"	"	1	241	231	6	40
"	900	1	270	262	6	44
"	"	1	267	255	5	57
"	850	3	269	261	6	43
"	"	3	260	252	6	48
"	900	3	273	267	5	57
"	"	3	269	266	4	57
"	850	10	272	270	6	50
"	"	10	273	275	5	49
"	900	10	275	268	4	50
"	"	10	274	270	5	50
1600	850	1	207	196	6	46
"	"	1	214	200	7	41
"	900	1	239	221	8	38
"	"	1	240	220	8	44
"	850	3	239	224	6	40
"	"	3	232	218	9	43
"	900	3	253	244	6	55
"	"	3	254	231	6	55
"	850	10	249	240	6	43
"	"	10	248	237	6	55
"	900	10	264	253	4	50
"	"	10	262	256	4	51

TABLE 26

TRANSVERSE TENSILE PROPERTIES OF WARM WORKED 18% NICKEL ALLOY (250 KSI)

Warm Work Temp. °F	Marage Temp °F	Marage Time Hours	Ult. Tens. Str. KSI	0.2% Yield Str. KSI	% Elong	% R.A.
1200	850	1	182	175	10	45
"	"	1	174	174	13	43
"	900	1	188	177	15	51
"	"	1	183	163	18	59
"	850	3	188	171	16	56
"	"	3	180	165	12	58
"	900	3	184	175	17	70
"	"	3	182	161	17	65
"	850	10	171	160	16	45
"	"	10	157	136	17	57
"	900	10	172	159	11	46
"	"	10	174	159	17	51
1400	850	1	240	231	7	36
"	"	1	238	221	6	33
"	900	1	256	251	6	47
"	"	1	258	246	6	47
"	850	3	265	260	7	46
"	"	3	263	250	6	32
"	900	3	286	270	5	49
"	"	3	267	264	5	56
"	850	10	273	267	6	44
"	"	10	270	262	6	48
"	900	10	271	269	4	46
"	"	10	273	268	4	47
1600	850	1	242	237	6	42
"	"	1	213	197	8	41
"	900	1	240	222	7	39
"	"	1	233	216	9	48
"	850	3	243	236	4	29
"	"	3	228	207	6	42
"	900	3	254	244	5	55
"	"	3	245	235	5	51
"	850	10	281	266	5	45
"	"	10	250	245	7	22
"	900	10	264	257	5	48

Table 27

EFFECT OF MARAGING TREATMENT ON FRACTURE TOUGHNESS
OF WARM WORKED 18% NICKEL ALLOY * (250KSI)

Warm Working Temp. ^{o}F	Orientation of Specimen Axis to Rolling Direction	Maraging Temp. ^{o}F	Maraging Time Hrs.	0.2% Yield Str. KSI	Net Fracture Stress (1) KSI	Notch Str. (2) KSI	β (3)	Critical Crack Index (4) in	K_c (5) $\frac{KSI}{\sqrt{in}}$	Gc (6) † in.lb/in^2
1200	Parallel	900	10	172		169**				
	"			172		170**				
1400	Parallel		3	267	246	205	3.13	1.16	204	1611
	"			267	244	213	2.84	1.13	202	1589
	Normal			267	257	203	3.83	2.08	216	1808
	"			267	237	199	2.76	1.05	199	1535
	Parallel		10	269	223	190	1.77	0.67	178	1234
	"			269	223	179	3.62	0.14	175	1190
	Normal			269	262	182	1.39	0.54	169	1103
	"			269	228	169	1.82	0.69	180	1256
1600	Parallel			255	242	194	5.45	0.20	201	1570
	"			255	236	193	5.22	0.19	198	1520

* Allegheny Heat No. 23832

† Centrally notched, fatigue cracked specimens

** Specimens tore through pin hole

Table 28

HEAT TREAT RESPONSE OF A THICK SECTION**
OF 18% Ni ALLOY (250 KSI)*

Specimen Location in Cube***	U.T.S. KSI	0.2% Yield Str. KSI	% Elong.	Red. in Area**** %
Surface	279	272	8.5	38.6
	277	268	8.0	31.2
Center	274	266	9.0	36.8
	278	270	8.0	30.3

* Allegheny Heat No. 23832

** Cube dimensions: 4½" x 4½" x 5¼"

*** Specimen machined parallel to flow lines at both ends

**** H.T.: Soln: 1500°F/1 hr.
Marage: 900°F/3 hrs.

(1 hr./in. thickness allowed at respective temperatures)

TABLE 29

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF
18% (250 KSI) MARAGING NICKEL STEEL

Smooth Bar Tensile Data

Location	% Reduction	Heat Treatment	U.T.S. (KSI)	0.2% Y.S. (KSI)	% Elong.	% R.A.
Billet						
Vertical-Center	0	1500°F/1 hr.	276.9	268	10	56.5
Vertical-Edge	0	900°F/10 hrs.	266.8	260.6	11.5	55.9
Horizontal-Center	0		278.5	268.6	9	44.7
Horizontal-Edge	0		273	263.7	9.5	46.7
First Upset						
Vertical-Center	33.8		270.5	263.7	11	56.7
Vertical-Edge	33.8		267.5	259.5	11.5	57.9
Horizontal-Center	33.8		237.1	222.7	16	55.8
Horizontal-Edge	33.8		268.5	258.5	10.5	49.9
Second Upset						
Vertical-Center	50		273.8	264.5	11	50.1
Vertical-Edge	50		274.3	266.7	12	51.1
Horizontal-Center	50		262.4	255.9	11	46.5
Horizontal-Edge	50		271.3	262.5	9.5	43.7
Third Upset						
Vertical-Center	66.2		274	273.6	9.5	41.6
Vertical-Edge	66.2		269.6	266.8	12.3	54
Horizontal-Center	66.2		233.1	223.4	14	53.5
Horizontal-Edge	66.2		229.7	216.9	14	58
Fourth Upset						
Vertical-Center	75		267.6	265.9	9.3	54
Vertical-Edge	75		270.4	268.2	10.8	59
Horizontal-Center	75		232.9	218.4	12	59.1
Horizontal-Edge	75		234.5	216.4	14	58.5
Fifth Upset						
Vertical-Center	84		279.0		15.5	50.3
Radial	84		239.2	225.3	13	59.4
Circumference	84		236.9	216.4	17	61.7

TABLE 29 (Cont'd.)

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF
18% (250 KSI) MARAGING NICKEL STEEL

Notch Bar Tensile Data

Location	% Reduction	Heat Treatment	U.T.S. (KSI)	K_{Ic} (KSI $\sqrt{\text{In}}$)	G_{Ic}
First Upset					
Vertical-Center	33.8	1500°F/1 hr.	385.2	79.7	247
Vertical-Edge	33.8	900°F/10 hrs.	380.8	78.9	241
Horizontal-Center	33.8		379	78.5	240
Horizontal-Edge	33.8		349.8	72.4	203
Second Upset					
Vertical-Center	50		378.4	78.4	238
Vertical-Edge	50		379.6	78.6	240
Horizontal-Center	50		371.4	76.9	229
Horizontal-Edge	50		369.4	76.5	228

Table 30

COMPARISON OF SHEET AND BAR STOCK TENSILE PROPERTIES
OF 18% NICKEL ALLOY* (250 KSI)

		Tensile Properties of Bar Stock				Tensile Properties of Sheet Stock			
Sol'n** Temp. °F	Sol'n Time Hrs.	U.T.S. KSI	0.2% Y.S. KSI	Elong. %	Red. In Area %	U.T.S. KSI	0.2% Y.S. KSI	Elong. %	Red. In Area %
1400	1 hr.	251	229	15	59	272	267	1.5	44
		251	235	15	52	288	276	4.0	46
						279	274	4.0	46
						275	266	2.0	47
1500	½ hr.	267	251	11	64	267	257	5.7	60
	½ hr.	279	265	10	60	275	263	5.5	51
1500	1 hr.	259	245	11	54	255	243	5.0	57
		257	245	16	56	258	247	5.0	58
		267	251	14	56	257	249	3.9	55
		261	244	12	62	258	251	5.0	57

* Allegheny Ludlum Heat No. 23832

** All specimens maraged @ 900°F for 3 hours

TABLE 31

Critical Fracture Toughness**
Parameters of 18% Nickel Alloy* (250 KSI)

Condition	Heat Treat	N.T.S. KSI	$K_{1}C$ KSI $\sqrt{In}$	$G_{1}C$ in-lb/in^2	$\frac{N.T.S.}{U.T.S.}$
Annealed	Sol'n.: 1500°F/1 Hr.	340	65.1	164.1	1.50
	Marage: 900°F/3 Hrs.	335	63.4	155.9	1.30
		344	65.8	168.0	1.34
30% Cold Work	Marage: 900°F/1.75 H.	398	82.5	263.9	1.38
		379	78.6	239.3	1.31
40% Cold Work		391	81.1	254.6	1.29
		392	81.3	255.9	1.30
50% Cold Work		409	84.8	278.6	1.33
		398	82.5	263.9	1.30

* Allegheny Heat No. 23832.

** Critical fracture toughness calculated from circumferentially-notched tensile bars ($K_t = 10$).

Table 32

WELD HARDNESS DATA - DPH (1)
18% NICKEL ALLOY (250 AND 300 KSI) - VERTICAL TRAVERSES (2)

Base Material	300 KSI				250 KSI			
Filler Wire	300KSI (7C-054)		Cast (7C-053)		300 KSI (7C-054)		250KSI (7C-055)	
Conditions (3)	As-Welded	Maraged	As-Welded	Maraged	As-Welded	Maraged	As-Welded	Maraged
Distance From Top of Weld In.								
.020	347	546	326	546	322	521	312	529
.040	357	569	330	551	326	533	330	513
.060	336	579	334	513	345	509	336	538
.080	322	551	361	569	332	525	334	517
.100	316	565	341	555	341	529	314	521
.120	320	574	354	609	--	521	--	542
.140	330	560	345	593	326	505	328	551
.160	343	593	336	603	318	521	316	517
.180	334	560	334	603	326	525	318	509
.200	334	583	336	603	324	529	320	517
Average-DPH	333.9	568	339.7	574.55	328.9	521.8	323.1	525.4
Rc Converted	34	53	34.7	53.7	33.5	50.5	32.7	51

(1) Diamond Pyramid Hardness - 10 KG load, 136^{o} apex angle.

(2) Vertical traverse - top to bottom along weld centerline.

(3) Marage: $900^{o}F$/3 hrs.

Table 33

WELD HARDNESS DATA

18% NICKEL ALLOY (300 and 250 KSI) - HORIZONTAL TRAVERSE (1)

Base Material	Filler Wire	Condition (3)	Hardness - DPH (2) Distance from Weld Centerline - In. 0	.020	.040	.060	.080	.100	Average DPH	Average Rc (Converted)
300 KSI	7C-054(4)	As-Welded	330	328	335	333	341	332	333	34
		Aged	565	584	589	579	574	--	578	54
	7C-053	As-Welded	341	328	334	324	330	330	331	33.6
		Aged	569	555	579	583	583	--	574	53.7
250 KSI	7C-054(4)	As-Welded	335	323	314	312	323	--	321	32.5
		Aged	534	523	519	534	534	--	529	51
	7C-055	As-Welded	328	314	312	326	326	--	321	32.5
		Aged	521	538	529	533	529	--	530	51.1

(1) Traverse taken along weld midpoint line

(2) Diamond Pyramid Hardness, 10 KG load, 136° apex angle

(3) Aged: 900°F/3 hours, Air Cool

(4) Average of two surveys

Table 34

WELD HEAT AFFECTED ZONE HARDNESS DATA - DPH (1)
18% NICKEL ALLOY (250 KSI) - HORIZONTAL TRAVERSE (2)

Base Material	Condition(3)	Distance From Weld Interface - in. .015	.030	.045	.060	.075	.090	.105	.120	.135	.150	.165	.180	.195	.210	.225	.240	.255	.280	.305	.330	.355	.380	.405
Solution Heat Treated	As-Welded	303	303	301	312	314	312	318	296	307	312	310	316	310	320	350	411	394	378	350	341	339	-	-
	Aged	525	529	538	521	525	533	521	538	538	560	536	551	551	551	509	521	529	525	529	529	542	533	542
40% Cold Worked	As-Welded	303	310	316	312	320	322	332	339	341	347	368	432	525	505	458	448	426	400	411	402	432	-	-
	Aged	525	538	542	493	525	521	525	551	574	574	565	529	559	593	593	598	609	604	598	603	588	603	-

(1) Diamond Pyramid Hardness, 10KG load, 136° apex angle

(2) Traverse taken along sheet centerline

(3) Aged: 900°F/3 hrs., air cool

Table 35

TRANSVERSE WELD TENSILE PROPERTIES
18% NICKEL ALLOY (250 KSI) - SOLUTION HEAT TREATED 0.140" SHEET (1)

Filler Wire		Marage						Average Properties					
Type	Heat No	Temp °F	Time Hrs.	UTS KSI	0.2% YS KSI	Elong %	R.A. %	UTS KSI	0.2% YS KSI	Elong %	R.A. %	Joint Eff.-% T.S.	Joint Eff.-% Y.S.
300 KSI	7C-054	900	3	253	250	2.8	14	256	253	2.9	14	96	100
				259	256	2.9	14						
		900	10	268	264	3.0	18.7	269	266	3.3	21.6	98	101
				270(2)	266	3.5	18.5						
				270(2)	267	3.5	26.5						
Cast	7C-053	900	3	246	233	3.0	20	246	235	3.1	18	93	93
				246	237	3.2	16						
		900	10	268	265	2.5	14.9	269	265	2.5	17.8	98	100
				270	264	2.5	20.7						
250 KSI	7C-055	900	3	238	231	3.7	21	241	232	3.6	21.5	91	92
				243	232	3.5	22						
		900	10	266	249	2.5	16.6	265	256	2.8	18.4	96	97
				264	262	3.0	20.1						
Cast	33179	900	10	273	267	2.5	14.3	273	268	2.8	16.1	99	102
				273	269	3.0	17.8						

(1) Sheet rolling direction parallel to orientation of specimen axis

(2) Specimens failed in base metal, all others failed in weld

Table 36

TRANSVERSE WELD TENSILE PROPERTIES
18% NICKEL ALLOY (250 AND 300 KSI) - SOLUTION HEAT TREATED 0.070" SHEET (1) (2)

Base Material	Filler Wire Type	Filler Wire Heat No.	Marage Temp. °F	Marage Time Hrs.	UTS KSI	0.2% Y.S. KSI	Elong. %	R.A. %	Average Properties UTS KSI	Average Properties 0.2% Y.S. KSI	Average Properties Elong. %	Average Properties R.A. %	Joint Eff-% T.S.	Joint Eff-% Y.S.
300 KSI	300KSI	7C-054	900	3	265	265	1.8	26.0	261	262	1.6	20.8	89	92
					262	262	1.8	23.0						
					257	262	1.5	22.3						
					239	257	1.5	10.6						
	Cast	7C-053	900	3	256	257	1.5	15.7	257	258	1.5	16.2	88	91
					258	259	1.5	16.7						
250 KSI	300KSI	7C-054	900	10	269	268	1.0	13.1	270	269	1.0	13.2	98	102
					271	269	1.0	13.2						
	Cast	7C-053	900	10	250	250	2.0	12.9	249	249	2.0	14.5	91	94
					247	247	2.0	16.0						
	250KSI	7C-055	900	10	250	250	2.0	35.0	251	251	1.8	30.8	91	95
					252	252	1.5	26.6						

(1) Sheet rolling direction parallel to orientation of specimen axis.

(2) All specimens failed in weld.

Table 37

TRANSVERSE WELD TENSILE PROPERTIES

18% NICKEL ALLOY (250 KSI) - 40% COLD WORKED 0.140" SHEET (1) (2)

Filler Wire		Marage						Average Properties					
					0.2%				0.2%			Joint Eff. %	
Type	Heat No.	Temp °F	Time Hours	UTS KSI	YS KSI	Elong %	R.A. %	UTS KSI	YS KSI	Elong %	R.A. %	TS	YS
300 KSI	7C-054	900	3	242	236	3.5	20	242	235	3.5	22	82	80
				242	233	3.5	24						
		900	1.75	249	250	4.0	26.4	255	256	3.5	22	86	88
				261	261	3.0	17.5						
Cast	7C-053	900	1.75	247	246	4.0	27.2	248	248	3.8	22.9	84	85
				249	250	3.5	18.5						
Cast	33179	900	1.75	245	246	4.0	22.8	246	247	3.8	22	83	85
				247	247	3.5	21.2						

(1) Sheet rolling direction parallel to orientation of specimen axis.

(2) All specimens failed in weld.

Table 38

TRANSVERSE WELD TENSILE PROPERTIES (1)
18% NICKEL ALLOY (250 AND 300 KSI) - 0.140" SHEET
SHEET ROLLING DIRECTION NORMAL TO ORIENTATION OF SPECIMEN AXIS

Base Material		Filler Wire		Marage						Average Properties					
Type	Condition(2)	Type	Heat No	Temp °F	Time Hours	UTS KSI	0.2% Y.S. KSI	Elong %	R.A. %	UTS KSI	0.2% Y.S. KSI	Elong %	R.A. %	Joint T.S.	Eff-% Y.S.
300 KSI	SHT	300 KSI	7C-054	900	3	282	278	2.4	12	274	269	2.3	11	92	91
						269	263	2.2	8						
						270	266	2.0	9.7						
						272	268	2.5	14.1						
300 KSI	50% CW	300 KSI	7C-054	900	3	277	275	2.2	8	275	272	2.2	7.5	76	76
						272	269	2.1	7						
				900	5.5	262	257	2.6	25	266	262	2.3	21.5	82	82
						270	267	2.0	18						
250 KSI	SHT	300 KSI	7C-054	900	3	257	255	2.3	18	254	253	2.7	17.5	96	97
						251	250	3.0	17						
				900	10	267	264	3.0	18	268	265	2.3	14.3	95	98
						269	266	1.5	10.6						
250 KSI	40% CW	300 KSI	7C-054	900	3	259	254	2.7	12	261	256	25.5	11	82	81
						262	257	2.4	10						
				900	1.75	234	231	4.0	35	234	231	3.7	33	76	76
						233	230	3.3	31						

(1) All specimens failed in weld

(2) SHT - Solution Heat Treated 1500°F/1 hr, Air Cool
CW - Cold Worked

* Allegheny Heat No. 23826

Table 39

LONGITUDINAL WELD TENSILE PROPERTIES
18% NICKEL ALLOY (250 AND 300 KSI) - SOLUTION HEAT TREATED 0.140" SHEET (1)

Base Material	Filler Wire Type	Filler Wire Heat No	Marage Temp °F	Marage Time Hours	UTS KSI	0.2% Y.S. KSI	Elong %	RA %	Average Properties UTS KSI	Average Properties 0.2% Y.S. KSI	Average Properties Elong %	Average Properties R.A. %	Joint Eff-% TS	Joint Eff-% YS
300 KSI	300 KSI	7C-054	900	3	285 280	277 270	5.5 6	27 23	283	274	6	25	95	93
	Cast	7C-053	900	3	271 284	267 273	5 5	22 24	278	270	5	23	93	92
	Cast	33179	900	3	287 280	276 268	5 6	25 28	284	272	5.5	26.5	95	92
250 KSI	300 KSI	7C-054	900	3	257 260	243 245	6 5	35 32	256	244	5.5	33.5	97	93
	Cast	7C-053	900	3	255 255	242 237	6 7	29 36	255	240	6.5	32.5	97	92
	250 KSI	7C-055	900	3	257 257	245 254	5 6	34 31	256	249	5.5	32.5	97	95

(1) Sheet rolling direction normal to orientation of specimen axis

TABLE 40

TRANSVERSE WELD FRACTURE TOUGHNESS PROPERTIES

18% NICKEL ALLOY (250 KSI) - 0.140" SHEET

FILLER WIRE TYPE	FILLER WIRE HEAT NO.	MARAGE TEMP. (°F)	MARAGE TIME (hrs.)	0.2% YIELD STR. (KSI)	NET FRACTURE STRESS (KSI)	NOTCH STRENGTH (KSI)	β	CRITICAL CRACK INDEX (in)	K_Q KSI $\sqrt{in}$	G_Q in-lb/in^2
Cast	7C-053	900	10	265	152.8	107.2	1.49	.056	111.2	479.4
				265	131.9	93.4	1.17	.042	96.5	361.1
300 KSI	7C-054 (1)	900	10	264	243.5	184.6	3.84	.171	193.5	1452*
				264	239.6	193.2	3.87	.171	193.5	1452*
250 KSI	7C-055	900	10	257	192.4	149.2	2.96	.166	148.1	849.7
				257	212.3	134.8	2.99	.110	151.2	886.4
Cast	33179	900	10	268	185.3	143.6	2.31	.087	140.5	764.8
				268	164.2	98.03	1.59	.056	112.0	495.9

(1) Both specimens notched partially in weld heat affected zone.

Table 41

COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE AND FRACTURE TOUGHNESS PROPERTIES
13% NICKEL ALLOY (250 KSI)

Base Material		Filler Wire		Marage		Average Weld Properties							Unwelded Sheet Properties					
Condition	Thickness in.	Type	Heat No.	Temp. °F	Time Hours	UTS KSI	0.2% Y.S. KSI	Elong. %	R.A. %	Joint Efficiency-% TS	Joint Efficiency-% Y.S.	K_c KSI $\sqrt{in}$	UTS KSI	0.2% Y.S. KSI	Elong. %	R.A. %	K_c - KSI $\sqrt{in.}$ Longitudinal	K_c - KSI $\sqrt{in.}$ Transverse
Solution Heat Treated (1)	0.140	250 KSI	7C-055	900	10	265	256	2.8	18.4	96	97	148-151	275	264	7	60	222-306	231-314
		300 KSI	7C-054	900	10	269	266	3.3	21.6	98	101	>129(2)						
		Cast	7C-053	900	10	269	265	2.5	17.8	98	100	97-111						
		Cast	33179	900	10	273	264	2.8	16.1	99	102	112-141						
40% Cold Worked	0.140	300 KSI	7C-054	900	1.75	255	256	3.5	22.0	86	88	-	295	292	-	-	180-190	100-120
		Cast	7C-053	900	1.75	248	248	3.8	22.9	84	85	-						
		Cast	33179	900	1.75	246	247	3.8	22.0	83	85	-						
Solution Heat Treated (1)	0.070	250 KSI	7C-055	900	10	231	231	1.8	30.8	91	93	-						
		300 KSI	7C-054	900	10	270	269	1.0	13.2	98	102	-						
		Cast	7C-053	900	10	249	249	2.0	14.5	91	96	-						

(1) Unwelded sheet solution heat treated 1500°F/1 hour

(2) Estimated on basis of fracture toughness level of the wire deposited on 300 KSI alloy sheet (Table 3.3.26)

3.3 18% Nickel Alloy (300 KSI)

The results of the effect of the various heat treating parameters on the hardness, mechanical properties, and fracture toughness of 18% nickel alloy (300 KSI) in the various conditions are presented in the next few sections. Before discussing the results, it is mentioned that the responses for this alloy are very similar to the 18% nickel alloy (250 KSI) with one big exception: the yield response is higher and the fracture toughness is, in general, lower at the high yield strength levels due to the higher titanium and cobalt contents.

3.3.1 Solution Annealed Condition

3.3.1.1 Effect of Solution and Maraging Parameters on Hardness

The "as-quenched" hardness response data after solution annealing at various conditions are plotted in Figure 77 and the individual hardness values are given in Table 42. The effect of maraging temperature and time on the hardness of solution annealed (1500°F/1 hr) are given in Figure 78 and Table 43.

Both the hardness curves show striking similarities to the hardness of 250 KSI nominal yield strength alloy. The maximum for the hardness again seemed to be between solutioning temperature of 1400°-1700°F and between the maraging temperatures of 850°F and 950°F. These temperatures were selected for more extensive evaluation of the sheet tensile data.

3.3.1.2 Effect of Solution Treating Parameters on the Sheet Tensile Properties

Figures 79, 80, and Tables 44 and 45 present the longitudinal and transverse tensile properties as a function of solution temperature. The strength values dropped about 20,000 psi when the solution annealing was increased from 1400°F to 1500°F.

The longitudinal and transverse tensile properties are plotted as a function of solutioning time in Figures 81 and 82. The results are also given in Tables 44 and 45. From the data, it was concluded that a solution treatment of 1500°F for 1 hour was sufficient to dissolve all the chemical heterogeneities and still give a fine, uniform grain size.

3.3.1.3 Effect of Solution Parameters on the Fracture Toughness

The longitudinal and transverse toughness are compared at two solutioning temperature and time levels in Figure 38. The effect of solu-

tioning on the fracture toughness is presented in Table 46. The average longitudinal K_c value shows a very sharp drop from 220 KSI $\sqrt{in.}$ to 83 KSI $\sqrt{in.}$ when the solutioning temperature is changed from 1500°F to 1400°F. Changing the holding time from 1 hour to ½ hour further reduces the longitudinal value to 185 KSI $\sqrt{in.}$ Since the crack propagation resistance is very critical at these high strength levels, it is suggested that the solution temperature of 1500°F and 1 hour should be maintained for annealing.

3.3.1.4 Effect of Solution Annealing Temperature on Microstructure

The effect of solution annealing temperature on the microstructure is shown in Figure 83. The heterogeneity and the indication of residual effects of working in the structure were much more pronounced in specimens solution annealed at 1400°F. There appeared to be considerable grain growth at the higher solutioning temperatures.

3.3.1.5 Effect of Maraging Parameter on the Tensile Properties of Solution Annealed Alloy

The longitudinal and transverse tensile properties are given in Tables 47 and 48. The longitudinal and transverse yield strengths are plotted as a function of maraging temperature in Figures 84 and 85. As discussed in Section 3.2.1.5, the maraging parameters were selected from the hardness data.

The longitudinal and transverse yield strength response surfaces are plotted as a function of maraging time and temperature in Figures 86 and 87. The yield strength surface responses are very similar to the 18% nickel (250 KSI nominal yield strength) alloy and the maximum response (297 KSI) occurred when the alloy was maraged at 900°F for 10 hours.

3.3.1.6 Effect of Maraging on Fracture Toughness

The fracture toughness data is reported in Table 49 and is plotted as a function of maraging time at 900°F in Figure 88 for both the longitudinal and transverse rolling direction. It is shown that as maraging time increases, toughness decreases in both directions. For a 10 hour marage, the K_c values in the longitudinal and transverse directions were reduced to 160 KSI $\sqrt{in}$ and 103 KSI $\sqrt{in}$, respectively. The K_c values were maximum for a 1 hour marage, being 220 KSI $\sqrt{in.}$ in the longitudinal direction and 183 KSI $\sqrt{in.}$ in the transverse direction. The 3 hour marage produced a longitudinal value of 183 KSI $\sqrt{in.}$ and transverse value of 157 KSI $\sqrt{in.}$

3.3.2 Cold Worked Condition

3.3.2.1 Effect of Cold Work on the Tensile Properties

The effects of cold work on strength were determined for five (5) levels of reduction namely, 20, 30, 40, 50 and 70 percent. Tables 50 and 51 report the effects of maraging temperature and time on the tensile properties of the 18% nickel alloy (300 KSI). The data are plotted in Figure 89 (longitudinal properties) and Figure 90 (transverse properties) for two maraging temperatures, 850°F and 900°F. It is shown that 850°F does not produce equivalent response to 900°F maraging in the longitudinal properties. For both maraging temperatures, maximum response is achieved at the 50% cold work level. However, the 900°F - 10 hour marage exhibits an ultimate tensile strength of 347 KSI versus 338 KSI for the 850°F marage. With lesser degrees of cold work and shorter maraging times the margin in strength between the two temperatures increases to approximately 25 KSI.

An important observation was made relative to maraging time at 900°F. Little difference between one (1), three (3) and ten (10) hours was observed. Conversely, the 850°F marage was highly dependent on time since differences as great as 50 KSI were obtained between a one hour marage and 10 hour marage for 20% cold worked material.

Transverse strengths are higher than longitudinal strengths. However, ductility is markedly decreased at all cold work levels and for both maraging temperatures. In general, the transverse properties are less responsive to cold work degree. Similar behavior to longitudinal strengths were observed for both maraging temperatures and also times studied.

Cold working produced significant increases in strength compared to solution and maraged strengths. However, the increased strength was balanced by a perceptible loss of ductility where high strength increases were achieved.

3.3.2.2 Optimization of Yield Strength Response of Cold Worked 18% Nickel Alloy (300 KSI)

Longitudinal yield strength response as a function of degree of cold work and the Larson-Miller parameter is plotted three dimensionally in Figure 91. This method of data presentation was used to analyze the data effectively and aid in visualizing the geometrical relations between yield strength response and the various parameters which govern response. Maragin tir e and temperature were expressed in the form of the empirical Larson-Miller parameter, P = °R (20 + log hours) x 10^{-3} and plotted against cold work percent to provide a

yield strength response surface shown in Figure 91. The surface indicates that the optimum yield strength response is at the 50% cold work level and a 28.2 Larson-Miller parameter level (see shaded area). With increasing cold work, the yield strength increases at a constant rate until it reaches a maximum at the 50% cold work level. Yield strength then declines at the higher cold work levels. As expected, the response surface reveals a very sharp rise between a "P" of 26.2 to 27.2. The rise in response is gradual from a "P" of 27.2 reaching the maximum ridge at the parameter level of 28.2, i.e., equivalent to 14.2 hours at 850°F; or to 5.4 hours at 900°F; or to 1 hour at 950°F. At higher levels of "P", the alloy structure overages and/or reverts to austenite. This occurrence is detected by a slight drop in strength.

3.3.2.3 Effect of Cold Work on Fracture Toughness Parameters

The effect of cold work degree and maraging parameters on longitudinal and transverse fracture toughness parameters are reported in Table 52. The fracture toughness parameter K_c as a function of cold work percent is plotted in Figure 92. Inspection of the accumulated data revealed that as cold work degree increased, fracture toughness decreased. For material cold reduced 20% the longitudinal K_c value averaged 204 KSI $\sqrt{\text{in.}}$ for a 900°F - 3 hour marage. At a 50% cold work level and comparable direction and heat treatment, the K_c value dropped to 101.5 KSI $\sqrt{\text{in.}}$ The curve in Figure 92 shows that fracture toughness increases from a cold work level of 50% to 70% (101.5 KSI $\sqrt{\text{in.}}$ to 123 KSI $\sqrt{\text{in.}}$). It is believed that the increase is a result of data scatter rather than true behavior since transverse behavior does not show a similar trend.

Cold work levels above 30% exhibited a pronounced reduction in fracture toughness levels. At this stage of the alloy's development, greater definition of high cold work levels is required before the strengths produced could be used for aerospace applications where toughness is critical.

3.3.3 Warm Worked Condition

3.3.3.1 Effect of Warm Work on the Tensile Properties

Longitudinal and transverse specimens were machined from sheets warm worked at 1200°F, 1400°F and 1600°F. Specimens were maraged at 850°F and 900°F in order to determine the effect of maraging on tensile properties. Times at the respective maraging temperatures were varied from 1 to 10 hours.

The tensile properties of warm worked 18% nickel alloy (300 KSI) are presented in Tables 53 and 54. The longitudinal and trans-

verse data are plotted in Figures 93 and 94. It is shown that maximum strength is exhibited by material warm worked at 1400°F regardless of maraging temperature and rolling direction. Optimum response is achieved by 10 hour maraging times for both 850°F and 900°F temperatures. Figure 95 shows the three dimensional response surface for yield strength as a function of the Larson-Miller parameter and warm working temperature. The yield strength response surface indicates the optimum response to be at the 28.56 parameter level. The yield strength increases sharply between 1200°F and 1400°F warm working temperatures. A maximum is attained at 1400°F followed by a decline as warm working temperature decreases. The increase in surface response is small with Larson-Miller parameter changes. The maximum parameter level of 28.56 is equivalent to 10 hours at 900°F.

3.3.3.2 Effect of Warm Work on Fracture Toughness

The effect of warm work temperature on fracture toughness parameters in the longitudinal and transverse rolling directions are tabulated in Table 55. The data are graphically illustrated in Figure 96 of the preceeding Section 3.2 - 18 % Nickel Alloy (250 KSI) for the maximum warm work response temperature of 1400°F. The results of this study indicate that the fracture toughness parameter K_c is low for all conditions of warm work and 900°F maraging times with the exception of a 900°F - 3 hour treatment for 1400°F warm work material. An average toughness level of K_c = 153 KSI $\sqrt{in.}$ was achieved by longitudinal specimens. Transverse specimens attained a K_c level of 138 KSI $\sqrt{in.}$ Consequently, it is concluded that the optimum warm work temperature studied was 1400°F when the material was subsequently maraged at 900°F for 3 hours.

3.3.4 Miscellaneous Mechanical Properties

3.3.4.1 Biaxial Strength

The purpose of the work presented in this section was specifically aimed at the development of shear spinning process parameters for 18% nickel, rocket motor case cylinder fabrication. In addition, the spun sub-scale cylinders were burst tested to obtain the ultimate burst strength and consequently, the degree of biaxial improvement over uniaxial strength.

The original purpose for initiating the program was further implemented by the Curtiss-Wright Corporation's decision to fabricate two full scale 18% nickel Pershing motor cases. The cylinder sections of these cases have been shearspun from forged and machined preforms.

a. Preform Preparation

Billet stock of the 300 KSI composition was procured from the Allegheny Ludlum Steel Corporation. Billets were shipped to the Taylor Forge and Pipe Works for forming into cylindrical forgings. All forgings were produced by back extrusion techniques. The starting temperature was 2200°F. Finishing temperature was 1700°F. Forgings were rough machined by Taylor Forge prior to shipment.

Rough machined forgings were solution treated at 1500°F for one hour. Base metal vessels were machined to the desired configuration. Two shearspinning preforms were obtained from one forging by sectioning the forging in half radially.

b. Shearspinning Procedure and Results

A total of four, six-inch diameter subscale vessels were spun on the Cincinnati Horizontal Hydro Spin Machine Figure 96. Two of the four vessels spun were of the 250 KSI, 18% nickel composition. The remaining vessels were of the 300 KSI, 18% nickel composition. Only 300 KSI vessels were burst tested.

Preform walls were machined to a 0.375" thickness. The final vessel wall thickness desired was 0.070". A four pass spinning operation, similar to the production Pershing process was chosen for the initial trials. Table 56 reports the settings subsequently used for spinning all vessels. R.P.M., roller nose radius and front roller lead were held constant for the four passes. An intermediate stress relief was incorporated after the second pass. The stress relief consisted of a 1500°F soak for one hour.

Each pass served an additional purpose other than reducing wall thickness. The first pass, at a feed rate of 7"/minute, served to break down the hot worked structure. The second pass, at 4"/minute, ring rolled the partially formed vessel to loosen it on the mandrel for ease in removal. The part was then stress relieved prior to the third pass. Tightening the part back on the mandrel was accomplished during the third pass by using a feed rate of 12"/minute. The final pass was conducted at 6"/minute to control the final part diameter. The total combined reduction of passes three and four was 68%.

c. Weld Procedure

The weld procedures used for vessels is reported in Table 57. In two instances repair welds were required. The repair weld procedures are reported in Table 58. Welds subsequently inspected were found sound.

d. Heat Treat Procedure

All solution treated vessels were maraged at 900°F for three hours after final machining.

Uniaxial tensile specimens representative of the same heat of material accompanied the vessels through the heat treat cycle. These uniaxial data are reported in Table 59 along with burst data.

e. Burst Test Procedure

The following facilities were required for the hydrotest of 6" diameter vessels:

1. High pressure pump capable of attaining and holding pressures up to 10,000 psig. Oil reservoir with a minimum capacity of 10 gallons located within test building.

2. One 0-10,000 psig Heisse Gage with follow-on, needle-transducer located as close to case as possible. Gage calibrated less than twenty-four hours before each test.

3. Test area which will safeguard personnel against flying shrapnel from burst cases and which can be closed off in order to keep out unauthorized personnel.

f. Pre-Test Procedure

1. The vessel was tested in a horizontal position; care was taken not to damage gages while installing the vessel in the cell. The two end closures were assembled to the vessel prior to installation of the vessel on the test stand.

2. The test medium for hydroburst was oil.

3. After installation of the vessel on the test stand, the vessel was filled with oil, insuring that all air pockets were purged. The test medium was at room temperature before filling the vessel.

4. The instrumentation was set up and checked.

5. Prior to starting the test the area was cleared of all unauthorized personnel and the area checked to insure that all test personnel were removed from the immediate vessel area and out of the line of fire.

6. The vessel was checked for leaks by pressurizing slowly to 1000 psig and holding for five minutes. If leaks were detected, pressure was released to zero psig and the leakage corrected. The procedure was repeated until the vessel was sealed.

7. After the pressure was released to 100 psig, the vessel was cycled three times between 100 psig and 1000 psig in a slow and continuous manner in order to condition the strain gages. The pressure was released slowly to zero psig following the third 1000 psig point.

g. <u>Hydroburst Procedure</u>

1. All gages were balanced: The CEC was checked for maximum span. A zero and a calibration reading were taken.

2. After insuring that all air pockets were purge pressurized slowly to 1000 psig and that all gages recorded on the CEC, the pressure was slowly released to 50 psig.

3. The vessel was pressurized to maximum psig (burst) by increasing the pressure from 50 psig to burst in a continuous manner. A Sprague air-operated pump (model S-216C-150) was used to deliver maximum volumetric capacity (approximately .21 G.P.M. at 4000 psig).

4. Pressure was recorded on the CEC as well as the Heisse gage mentioned in e.-2.

h. <u>Test Results</u>

Burst test results are presented in Table 59. Uniaxial ultimate and yield strengths obtained from specimens of the same heat, heat treated with their respective vessels are included.

The two forged and machined, unwelded vessels burst at 345 and 348 KSI based upon PR/t **(Figure 97)**. Strain gage analysis indicated unwelded biaxial ultimate tensile strengths of 332 to 342 KSI and 0.2% biaxial yield strengths of 326 to 330 KSI dependent upon the particular strain gage location. Biaxial gain, based upon burst (PR/t) ranged from 14.1 to 17.5% for ultimate strength and 16.2 to 17.6% for .2% yield strength. These values agree favorably with the theoretical biaxial improvement factor of 15%.

The two forged and machined girth welded vessels burst at 310.3 and 335 KSI based on PR/t (Figure 98). Strain gage analyses indicated

that the biaxial ultimate strength of the vessels ranged from 322.8 to 338 KSI, and biaxial 0.2% yield strengths from 327.5 to 328 KSI. These values represent a biaxial improvement in ultimate strength of from 16.7 to 16.9% and 0.2% yield strength of 15.8 to 17.5%.

A shear spun (68% reduction), maraged only (900°F-3 hrs.) vessel burst at 349 KSI. This vessel failed before reaching 0.2% yield as indicated by strain gage analysis. The degree of cold reduction produced a high burst but lowered ductility substantially. A similar burst was encountered with the shear spun (68% reduction, maraged 900°F-3 hrs.), girth welded vessel which burst at 302.7 KSI. The strain gage trace indicated that this vessel also failed to achieve 0.2% biaxial yield.

The results of subscale burst tests proved the capabilities of the 18% nickel alloy (300 KSI) in thin walled, ultra high strength rocket motor cases. Examination of the fracture surfaces of forged and machined vessels as well as shear spun vessels exhibited a shear mode of fracture indicative of high toughness. The exact cause of premature failure of the shear spun vessels is not known at this time. Interestingly, the fracture surfaces of the burst spun vessel exhibited shear failure indicative of good ductility and toughness.

3.3.4.2 Elevated Temperature Properties

The effect of test temperature on the tensile properties of the 18% nickel alloy (300 KSI) is presented in Figure 99. It is shown that ultimate and yield strength dropped sharply at a test temperature of 250°F. The decrease in strength continues as test temperature increases, but at a less drastic rate from 250°F (yield of 224.5 KSI) to 750°F (yield of 200 KSI). The rapid degradation in properties is encountered from 750°F to 1000°F (yield of 127 KSI). Surprisingly, ductility does not show a continuous increase, but rather, a relatively stable range of values from 250°F to 1000°F. It appears that reduction of area, which increased from 45% to 60% from room temperature to 250°F counters any increase in elongation caused by increased ductility with higher test temperatures.

The effect of solution time on the elevated temperature properties is shown in Figure 100 for test temperature of 1000°F. It appeared that 1500°F for 2 hours produced a better combination of yield to ultimate strength because of slightly increased grain coarsening imparting greater high strength stability. However, the data was considered insufficient for any firm conclusions to be made.

3.3.4.3 Heat Treat Response of a Thick Section

A 4.5-inch square by 5.25-inch long billet of the 18% nickel (300 KSI)

alloy was heat treated by solutioning at 1500°F/1 hour per inch of section plus maraging at 900°F. The hardenability of the alloy was measured by removing specimens from the surface and the center of the billet. The results are graphically reported in Figure 101. The strengths at both locations are comparable, indicating excellent hardenability. However, the ductility exhibited by the center specimens was drastically inferior to the surface. This is probably attributable to the lack of material conditioning by hot working in the interior of the billet.

3.3.4.4 Effect of Forging Reduction on the Properties of 18% Nickel (300 KSI) Alloy

A similar series of billet and pancake forgings as reported in Section 3.2.4.3 were evaluated for the 300 KSI composition. The results are tabulated in Table 60. Figures 102 through 105 show the effect of forging reduction on directional properties.

The 300 KSI composition exhibits similar strength consistency as a function of forging reduction. Also, a similar consistency of billet properties regardless of location or direction was obtained (approx. 280 KSI) indicating good billet conditioning. As was the case with the 250 KSI composition, insufficient data were available to establish firm trends in properties.

Notch bar properties ($K_t > 10$) shown in Table 60 indicate good toughness in all but the horizontal-center specimens representing a 33.8% reduction. Similar location specimens for a 50% reduction did not repeat the poor notch behavior. No definite conclusion as to the validity of the former data was possible since the data was limited.

3.3.4.5 Comparison of Sheet and Bar Properties

A comparison of sheet and bar properties was conducted to ascertain the validity of data interpretation between the two types of specimens. Figure 106 compares the sheet and bar properties for three different heat treat conditions.

The 1500°F solution treatment followed by 900°F-3 hour marage produced excellent correlation between sheet and bar strengths. Reduction in area values were comparable, however, elongation for the sheet specimens was perceptably lower. A 1400°F solution treatment (900°F-3 hr. marage) exhibited higher strengths in sheet form but substantially lower ductility. Incomplete homogenization of the structure is encountered with the low solution temperature.

3.3.4.6 Fatigue Properties

The smooth and notched R.R. Moore rotating beam fatigue, S-N curves are shown in Figure 107. The smooth endurance strength (10^8 cycles) was found to be 95,000 psi. For material solutioned at 1500°F/1 hour and maraged at 900°F/3 hours, the notched bar endurance strength (10^8 cycles) was found to be 65,000 psi for a notch $K_t = 2$.

Estimated 90% probability of survival curves indicate a level of 90,000 psi for smooth bar and 60,000 psi for notch bar data.

3.3.4.7 Impact Properties

Charpy impact strength as a function of cryogenic test temperature for solution treated and maraged material (1500°F-1 hour + 900°F-3 hours) is plotted in Figure 108. It is shown that impact strength falls rapidly from 74 ft.-lbs. at room temperature to 22 ft.-lbs. at -100°F. Impact strength then levels off, exhibiting 17.5 ft.-lbs. at -300°F.

Impact strengths of cold worked material (30 and 40% C.W.) are plotted as a function of cryogenic test temperature in Figure 109. Room temperature impact strength for 30 and 40% cold worked material were 23 and 20 ft.-lbs., respectively. Consequently, the fall in impact strength for cold worked material with decreasing test temperature shows a moderate slope. At -300°F however, impact strength for both cold work levels is below 5 ft.-lbs.

3.3.5 Summary Discussion

The combination of strength and fracture toughness exhibited by the 18% nickel (300 KSI) alloy evaluated during this program can be summarized by the data in Table 61. A comparison of fracture toughness and strength parameters as effected by various material conditions is offered. The data presented indicates that the 300 KSI composition solution and maraged material did not exhibit the greatest fracture toughness based on sharp notch round bar specimens. Material cold worked 30% and maraged at 900°F for 5.5 hours produced the best average K_{1c} value (85.3 KSI $\sqrt{\text{in}}$) and average notch ultimate to smooth ultimate ratio (1.27). Again, as with the 250 KSI composition, small amounts of cold work appear beneficial for improvement of the strength/toughness combination. A comparison of fracture toughness of the 300 KSI alloy in various conditions is presented in Figure 110 to justify this conclusion. It is shown that K_c for cold worked material is quite comparable to both annealed and warm worked material although at substantially higher yield strength levels.

The microstructure of the 300 KSI composition is presented in two conditions: solution annealed, solution annealed and maraged (Figures 111 and 112). Two magnifications are shown for each condition; 500 X and 18000 X.

The solution treated condition (Figure 111 exhibits a completely martensitic structure. The comparison between a 1500°F solution treatment and 1800°F solution treatment reveals the greater extent of grain coarsening produced by the higher temperature. Both structures show a high degree of solutioning by the absence of large amounts of precipitate structure.

The solutioned and maraged, and 30% cold worked and maraged structures are shown in Figure 112. The most perceptible distinction between the two structures is the finer structure exhibited by the cold worked material. The solutioned and maraged structure exhibits the previous structural effects of solutioning.

3.3.6 Weld Properties

Hardness and tensile properties for the 18% nickel alloy (300 KSI) welded in two material conditions (solution heat treated and cold worked) are presented in the following sections. The various filler materials investigated are also compared on the basis of fracture toughness.

3.3.6.1 Hardness Properties

Weld Zone

Vertical hardness traverses taken along the weld centerline for both the as-welded and maraged conditions are presented in Table 32. As shown in Figure 113, hardness after maraging is quite uniform across both weld passes. In addition, little difference in aged hardness was observed between the two filler wire deposits. Longitudinal weld hardnesses behaved similarly as shown in Table 33.

Heat-Affected-Zone

The results of longitudinal hardness surveys made on both solution heat treated and cold worked welded sheet are given in Table 62 and Figures 114 and 115. Examination of the plotted data reveal d that the weld heat-affected zone of the 300 KSI alloy experienced changes which closely paralleled those previously reported for the 250 KSI alloy. Aging was experienced in the heat-affected zone in both material conditions at a point approximately 0.175 inches from the weld interface. In these areas hardness increased from 36

to 49 R_c in the solution heat treated sheet (Figure 114), and from 42 to 52 R_c in the cold worked material (Figure 115). The increase noted in the solution heat treated 300 KSI alloy was greater than previously observed in the 250 KSI alloy (Figure 69), probably because of the more rapid aging response of the former. Response in the cold worked material heat-affected-zone was about the same in both 18% nickel alloys.

Maraging at 900°F equalized hardness in the weld heat-affected-zone in solution heat treated sheet at about 55 R_c (Figure 114). The heat-affected zone in cold worked material did not behave similarly, since the area closest to the weld interface was resolutioned. This area hardened to 55 to 56 R_c as compared to 59 R_c in the area of unaffected base metal (Figure 115).

As was the case in the 250 KSI alloy, the presence of a retained austenite band in the weld heat-affected-zone of the 300 KSI alloy was not established on the basis of the hardness surveys. No evidence of such an area was observed in the solution heat treated 300 KSI material. A suspected low point, approximately 0.200" from the weld interface was observed in the traverse on cold worked aged sheet (Table 97). However, this location would appear to have been subjected to peak maraging temperatures rather than the 1200-1300°F temperatures known to promote austenite stabilization.

3.3.6.2 Tensile Properties

The evaluation of welding filler materials on the 18% nickel (300 KSI) alloy was similar to that followed in Section 3.2.5.2 for the 250 KSI alloy.

<u>Solution Heat Treated Base Material (0.140" Sheet)</u>

Transverse weld tensile test data comparing various filler wire compositions are listed in Table 63 and represented graphically in Figure 116. In the case of the solution heat treated 300 KSI alloy, the final heat treatment of 900°F for 3 hours determined on the basis of base material studies, proved to be identical to that selected for the preliminary weld evaluations.

None of the filler wires tested deposited welds in solution heat treated sheet which achieved 100% weld yield strength joint efficiency. A maximum of 95% joint efficiency at a level of 269 KSI average yield strength was attained using the high cobalt cast composition wire (Figure 116). The matching 300 KSI filler wire composition exhibited the lowest tensile properties: 259 KSI yield strength and 91% joint efficiency. It should be noted, however that the superiority

of the cast composition wire is based only on average properties, since in some individual tests the 300 KSI filler wire welds showed greater strength (Table 63). Little or no difference in weld ductility was observed between welds made using the various filler wires.

Solution Heat Treated Base Material (0.070" Sheet)

Tensile properties of welds made in 0.070" thick sheet are given in Table 36 and Figure 72. In these thin sheet welds, the 300 KSI filler wire exhibited an average yield strength of 262 KSI slightly better than that attained in the 0.140" sheet (Table 63). Welds made using the cast copper-containing composition wire, however, showed a slight reduction in yield strength from 264 KSI in 0.140" sheet to 258 KSI. (Tables 63 and 36).

50% Cold Worked Base Material (0.140" Sheet)

Welds made in cold worked sheet and maraged at 900°F for 5.5 hours were evaluated on the basis of transverse weld tensile tests. The results of these tests are included in Table 64 and Figure 117. The performance of the various filler materials as based on yield strength was in the same order as observed in welds in solution heat treated sheet. Yield strengths ranged from 288 KSI (85% joint efficiency) for the high cobalt "cast" composition welds to 275 KSI (81% joint efficiency) for the matching base metal composition filler wires. Although tensile properties were increased in welds made in cold worked as compared to solution heat treated sheet, joint efficiencies were lower due to the accompanying greater increase in the baseline parent metal tensile properties (Tables 63 and 64).

Miscellaneous Weld Tensile Properties

The results of transverse tensile tests on welds made in both material conditions in 0.140" sheet with the direction of testing normal to the rolling direction are included in Table 38. Only welds produced using the 300 KSI filler wire were evaluated.

Comparison against data reported in Table 63 (sheet rolling direction parallel to test direction) showed an increase in yield strength from 259 to 269 KSI for welds made in solution heat treated material with rolling direction normal to test direction. Welds in cold worked sheet maraged 900°F/5.5 hours showed a drop in yield strength from 275 to 262 KSI similar to that noted in corresponding tests made on cold worked 250 KSI sheet (Table 38). Preliminary tests on a similar set of specimens in cold worked sheet which were maraged 3 hours at 900°F showed only a slight change in yield strength for

different rolling directions (Tables 64 and 38).

Longitudinal weld tensile test results are presented in Table 39 and Figure 74. Differences which existed in transverse yield strengths between welds produced with the various filler wires were not apparent in longitudinal tests. Longitudinal weld yield strengths varied only from 270 to 274 KSI, a level of approximately 92% joint efficiency (Table 39). These results represented an improvement over transverse weld properties particularly for the 300 KSI filler wire welds which increased from 259 KSI to 274 KSI.

3.3.6.3 Fracture Toughness

A comparison of weld filler materials on the basis of transverse weld fracture toughness properties is presented in Table 65. Figure 118 compares weld toughness on the basis of K_c values only. All test specimens were maraged at 900°F for 3 hours.

Maximum fracture toughness properties were obtained in welds made with the matching 300 KSI composition filler wire, which attained average K_c values of 137 KSI $\sqrt{in}$ Figure 118. This level of toughness compared reasonably well with base material fracture toughness reported in Table 49 of about 157 KSI $\sqrt{in}$ for the transverse rolling direction and 184 KSI $\sqrt{in}$ for the longitudinal rolling direction. Of the two cast-type filler wire compositions evaluated, the high cobalt, copper-free version (Heat No. 33179) exhibited slightly better toughness (Table 65). These results were consistent with those obtained in similar tests made on welds in 250 KSI sheet (Table 40).

3.3.6.4 Summary

In general, weldability of the 18% nickel alloy (300 KSI) was found to be equal to that reported for the 250 KSI alloy in Section 3.2.6.

Weld and heat-affected-zone soundness equal to that demonstrated by the 250 KSI alloy was consistently attained in all combinations of filler wire and base material conditions evaluated. This level of quality was achieved using conventional TIG welding procedures without benefit of a "preheat-interpass-postheat" weld thermal cycle.

A comparison of filler materials similar to that described for the 250 KSI alloy welds in Section 3.2.6.4 is presented in Figure 119 and Table 102.

On the basis of average transverse tensile data, the high cobalt, cast composition filler wire welds achieved the highest levels of

yield strength joint efficiency in both material conditions tested (Figure 119). The 300 KSI filler wire welds exhibited lower average strength, accompanied by some improvement in fracture toughness (Figure 119). For welding solution heat treated material the essentially matching composition filler wire appears to offer the best available combination of weld properties.

Welds made in cold worked materials using the cast composition wires demonstrated a definite superiority over the 300 KSI wire on the basis of transverse tensile results (Figure 119 and Table 66). In this case, the high cobalt wire may be preferred on the basis of its greater weld strength properties.

Solution Temperature - °F

HARDNESS RESPONSE CONTOURS OF SOLUTION ANNEALED
18% NICKEL ALLOY (300 KSI)

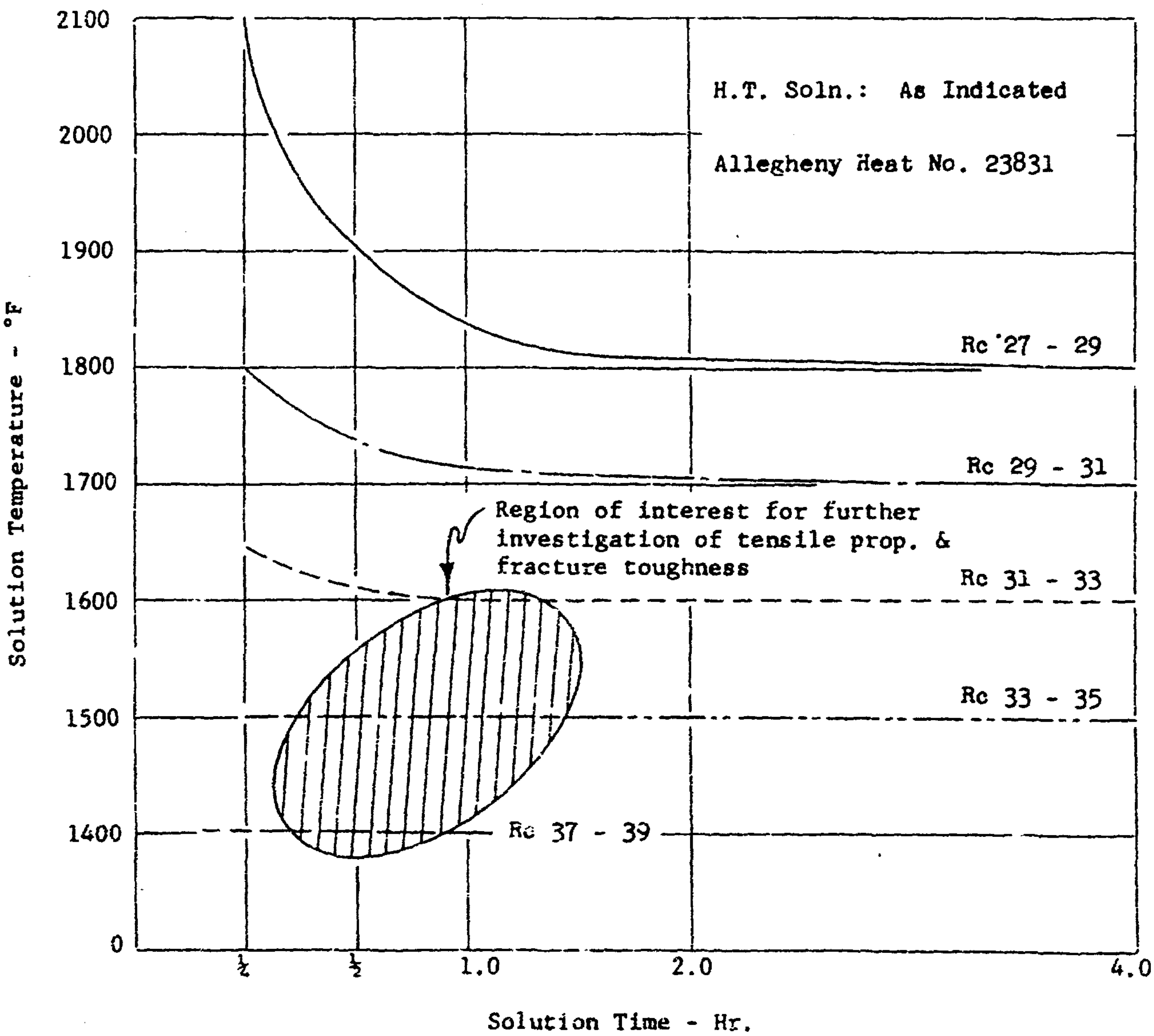


Figure 77

EFFECT OF MARAGING PARAMETERS ON THE HARDNESS OF SOLUTION TREATED 18% NICKEL ALLOY (300 KSI)

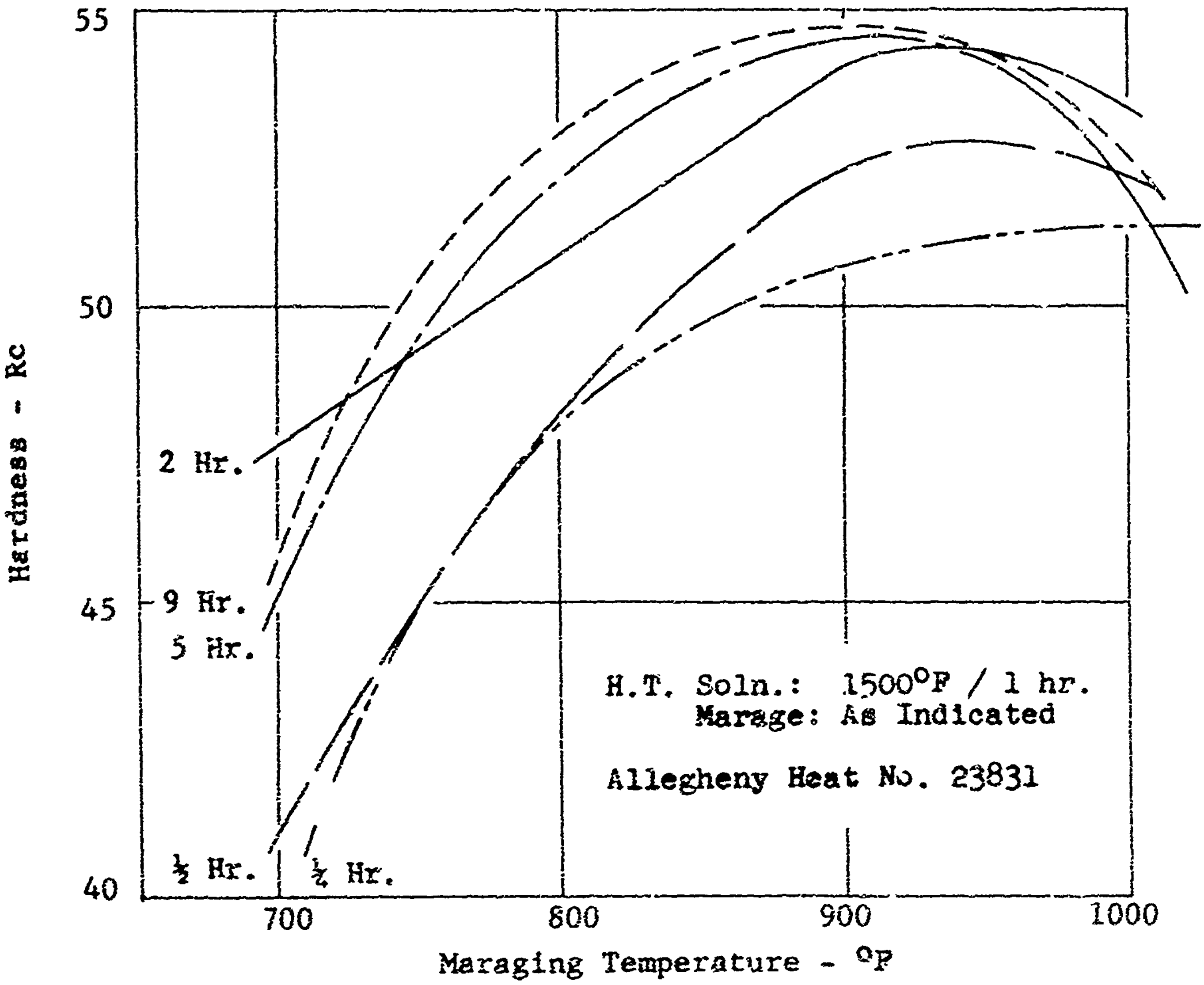


Figure 78

EFFECT OF SOLUTION TREATING TEMPERATURE ON
LONGITUDINAL TENSILE PROPERTIES OF
18% NICKEL ALLOY (300 KSI)

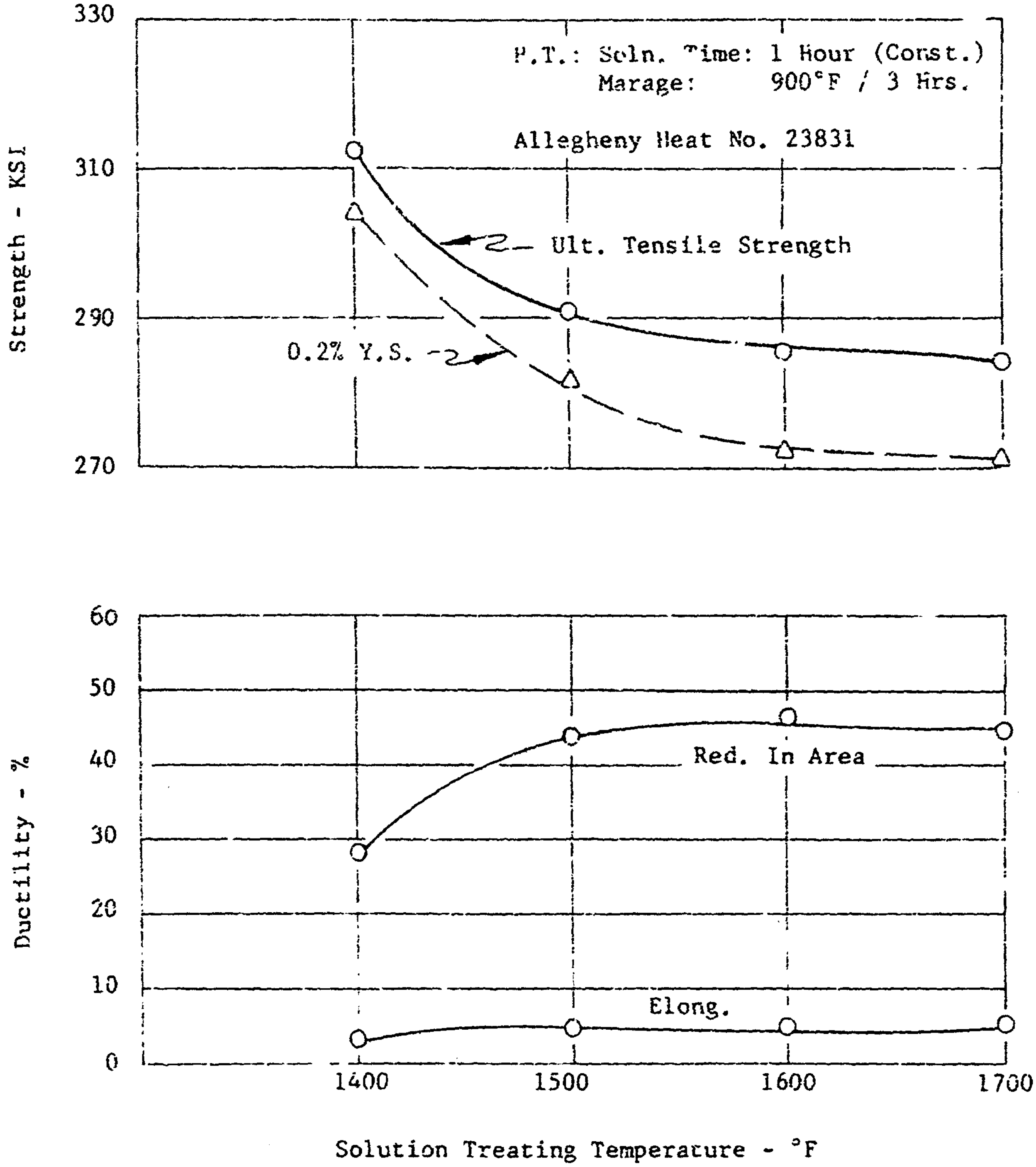


Figure 79

EFFECT OF SOLUTION TREATING TEMPERATURE ON TRANSVERSE TENSILE PROPERTIES OF 18% NICKEL ALLOY (300 KSI)

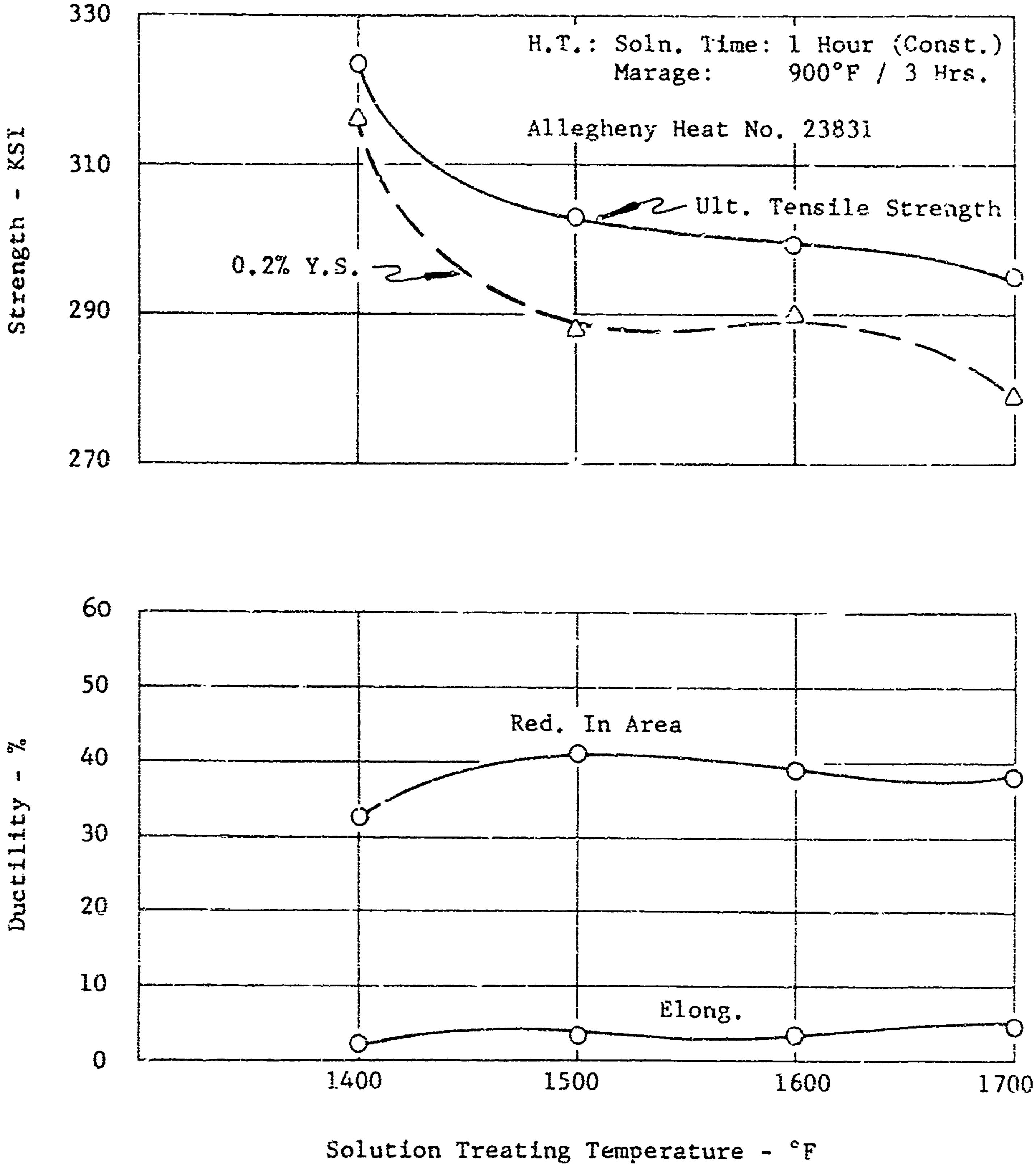


Figure 80

EFFECT OF SOLUTION TREATING TIME ON LONGITUDINAL TENSILE PROPERTIES OF 18% NICKEL ALLOY (300 KSI)

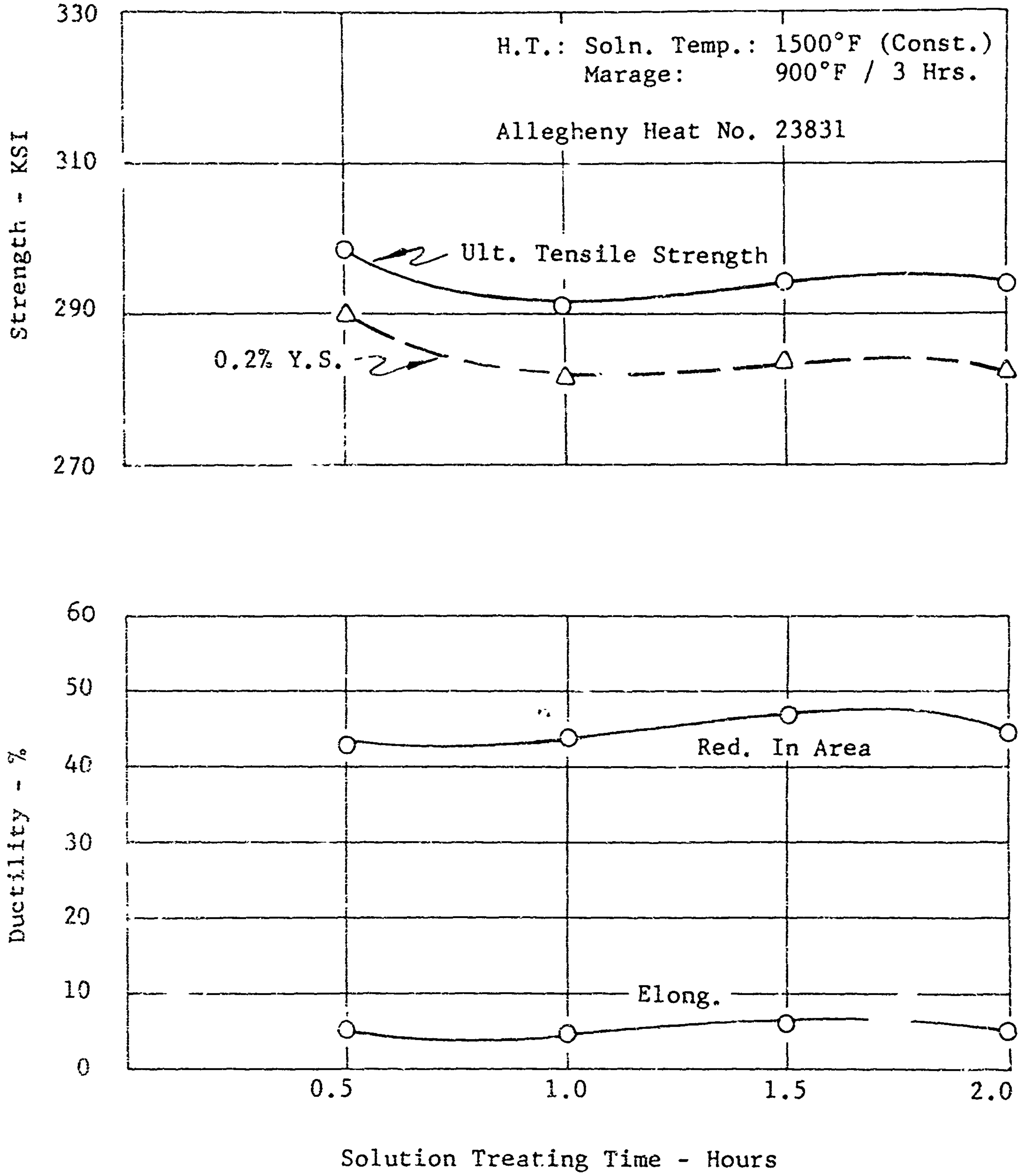


Figure 81

EFFECT OF SOLUTION TREATING TIME ON THE TRANSVERSE TENSILE PROPERTIES OF 18% NICKEL ALLOY (300 KSI)

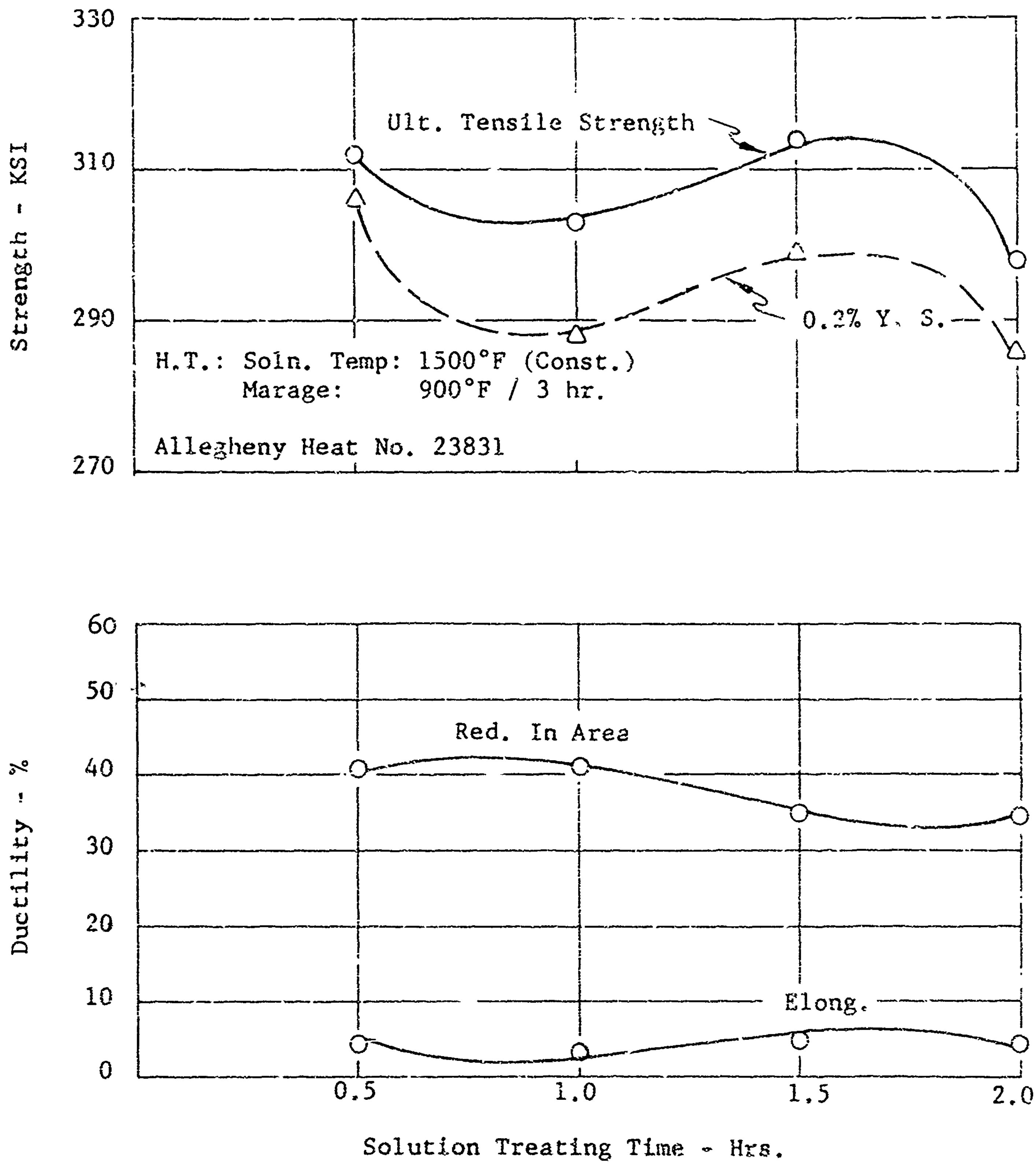


Figure 82

EFFECT OF SOLUTION TREATING TEMPERATURE ON MICROSTRUCTURE OF 18% NICKEL ALLOY (300 KSI)

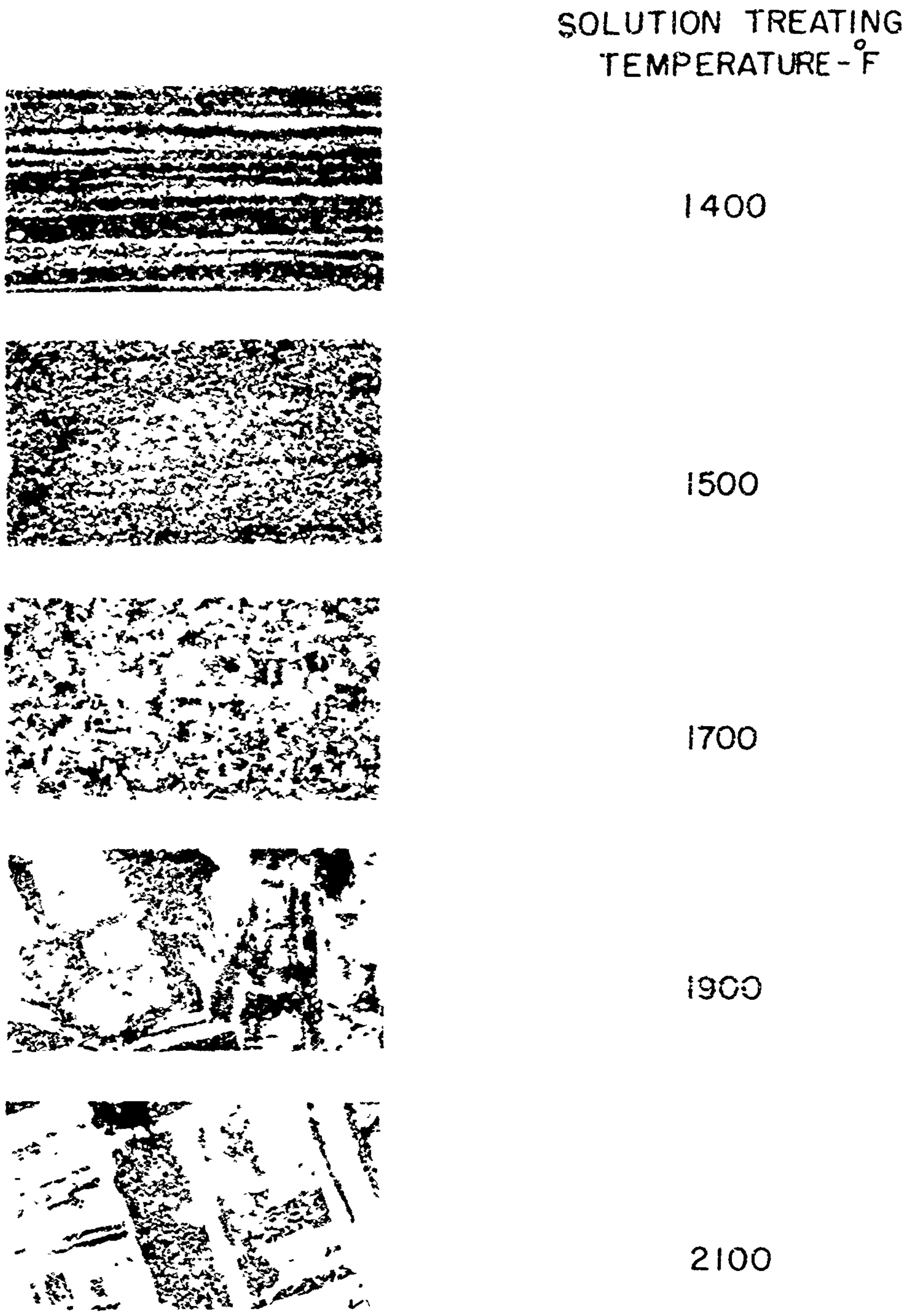


Figure 83

EFFECT OF MARAGING TREATMENT ON THE
LONGITUDINAL TENSILE PROPERTIES OF SOLN.
ANNEALED 18% NICKEL ALLOY (300 KSI)

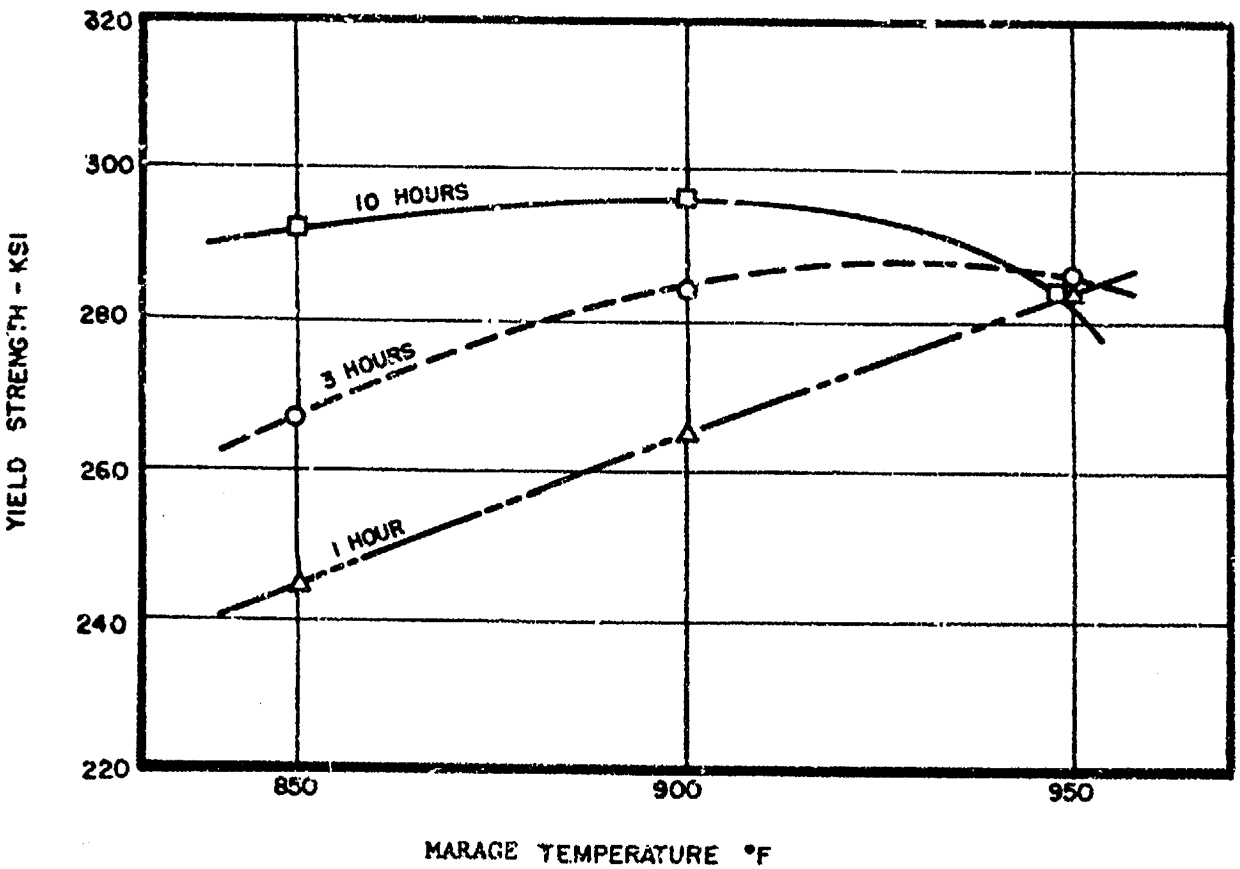


FIG - 84

176

~~Figure 84~~

EFFECT OF MARAGING TREATMENT ON THE
TRANSVERSE TENSILE PROPERTIES OF SOLN. ANNEALED
18% NICKEL ALLOY (300 KSI)

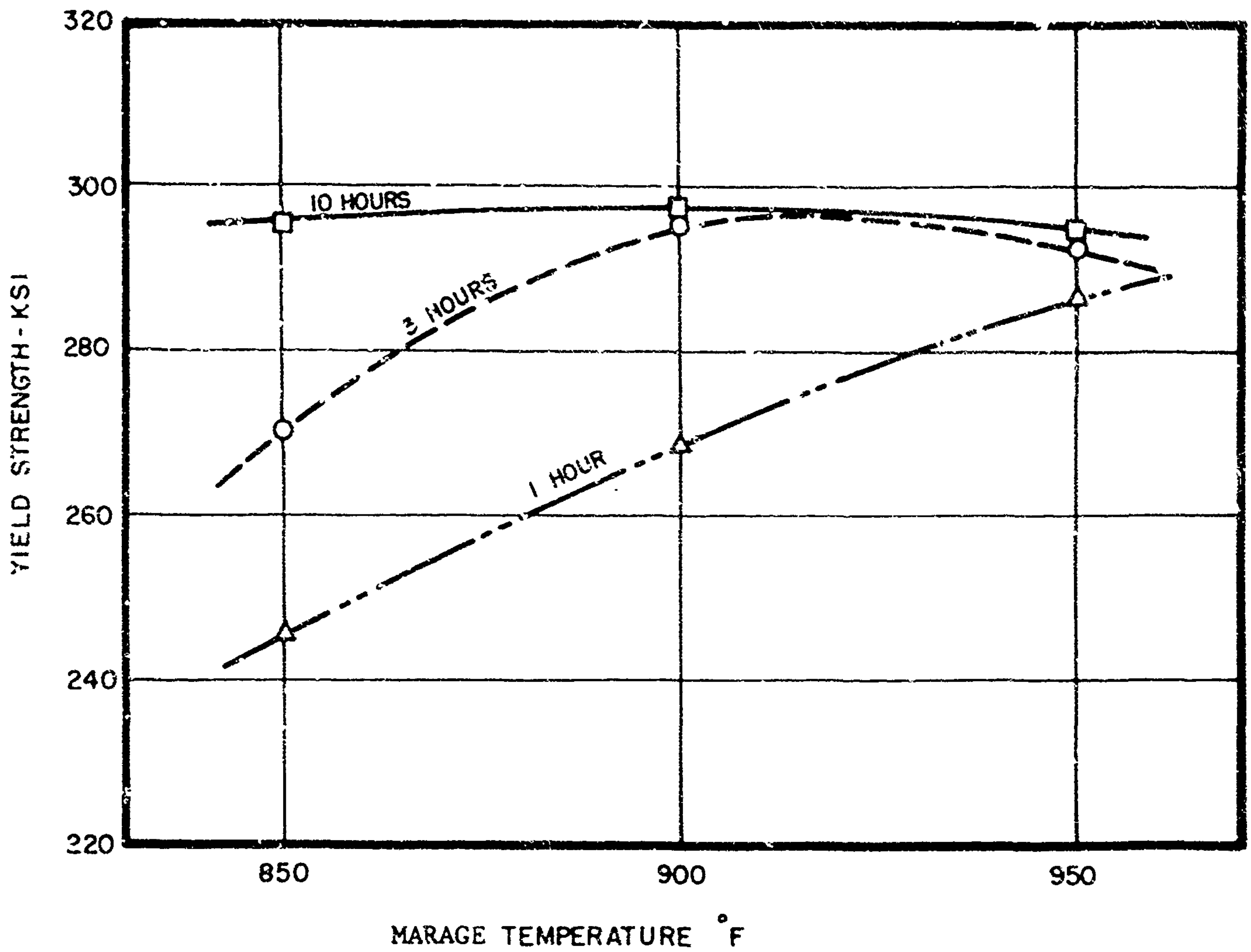
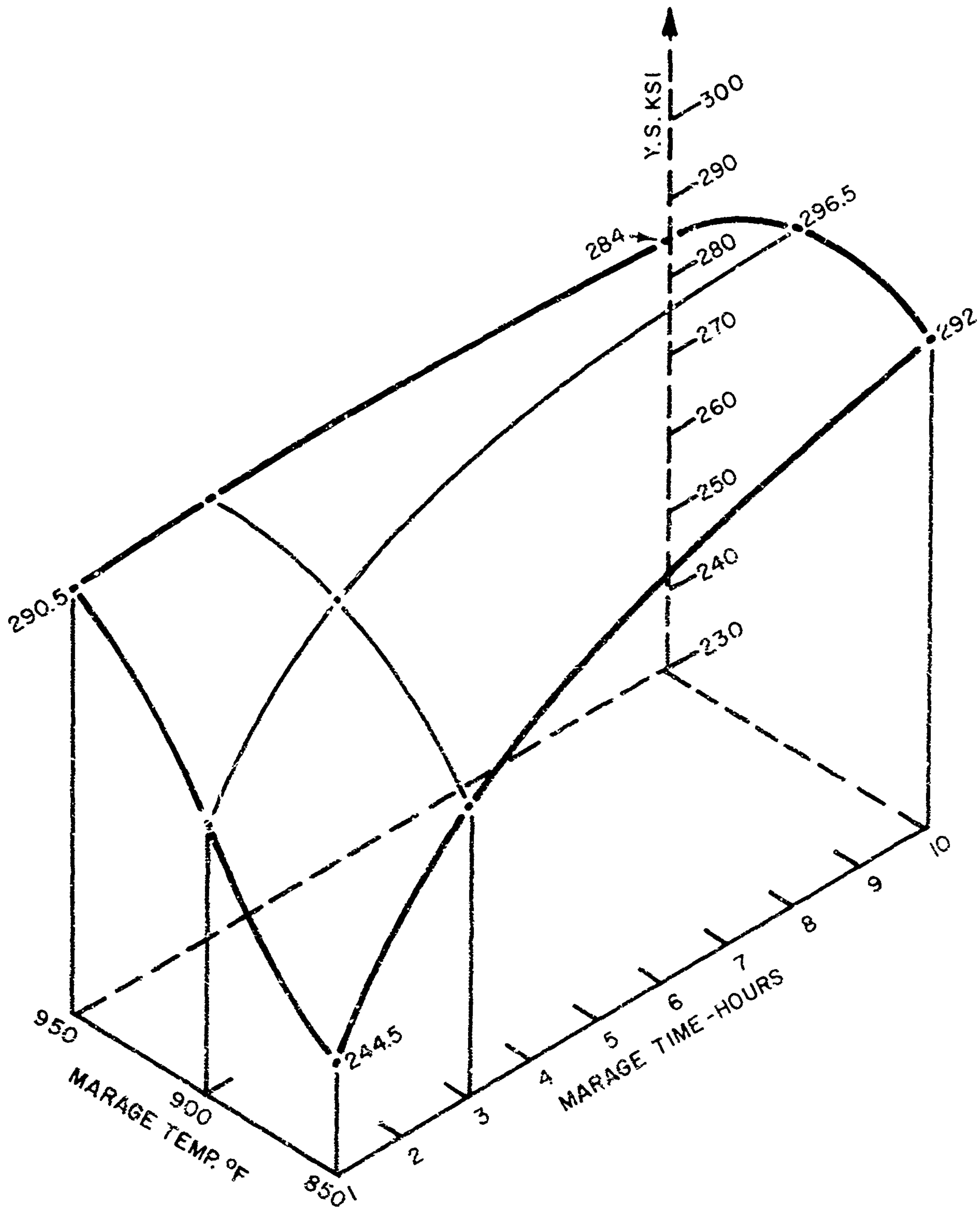


Figure 85

OPTIMIZATION OF LONGITUDINAL YIELD STRENGTH

RESPONSE OF SOLUTION ANNEALED 18% NICKEL ALLOY (300 KSI)



All Specimens Soln. Annealed: 1500°F / 1 hr. (argon)

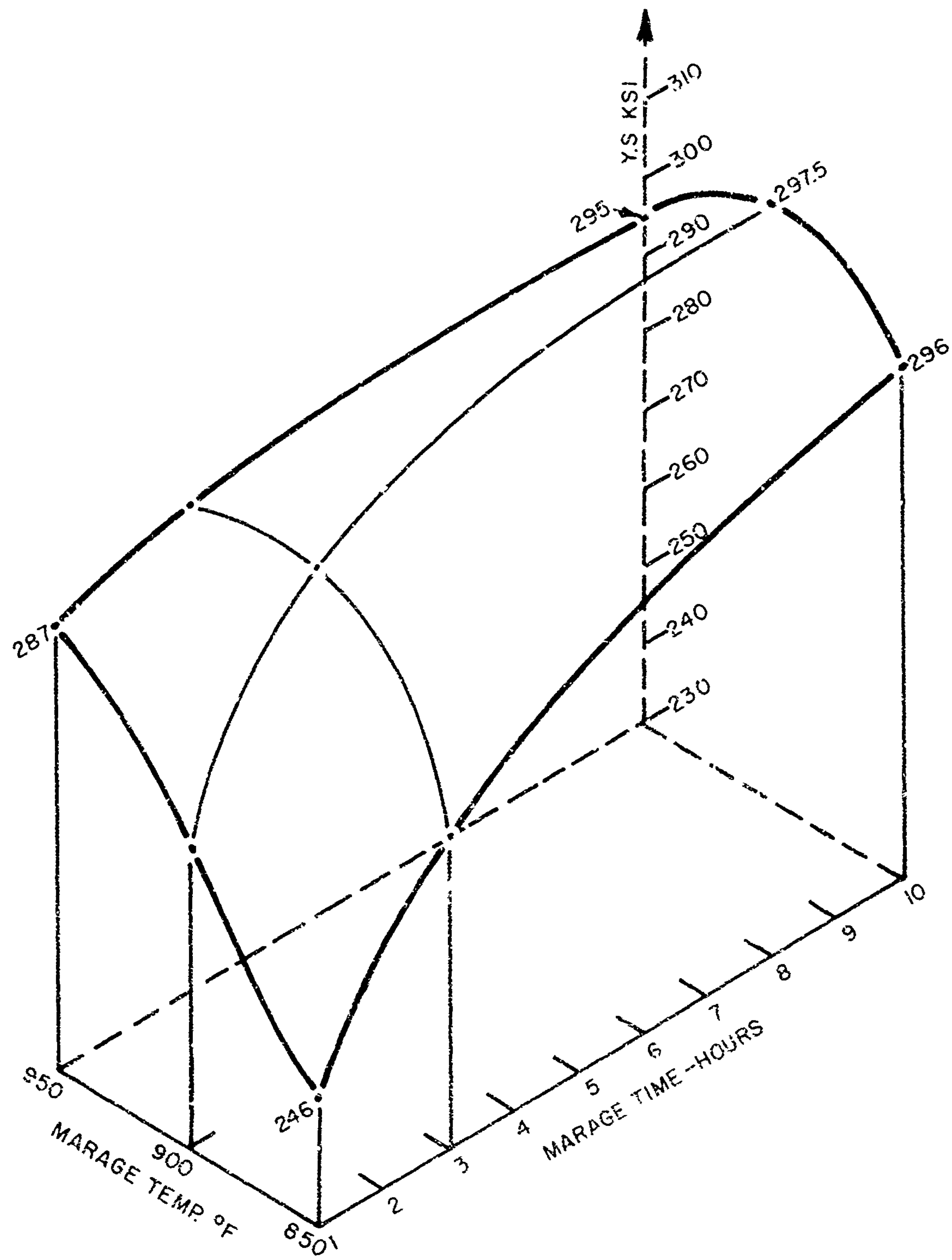
Allegheny Heat No. 23831

Figure 86

3395

OPTIMIZATION OF TRANSVERSE YIELD STRENGTH

RESPONSE OF SOLUTION ANNEALED 18% NICKEL ALLOY (300 KSI)



All Specimens Soln. Annealed: 1500°F / 1 hr. (argon)

Allegheny Heat No. 23831

Figure 87

EFFECT OF MARAGING TREATMENT ON FRACTURE
TOUGHNESS OF SOLUTION TREATED
18% NICKEL ALLOY (300 KSI)

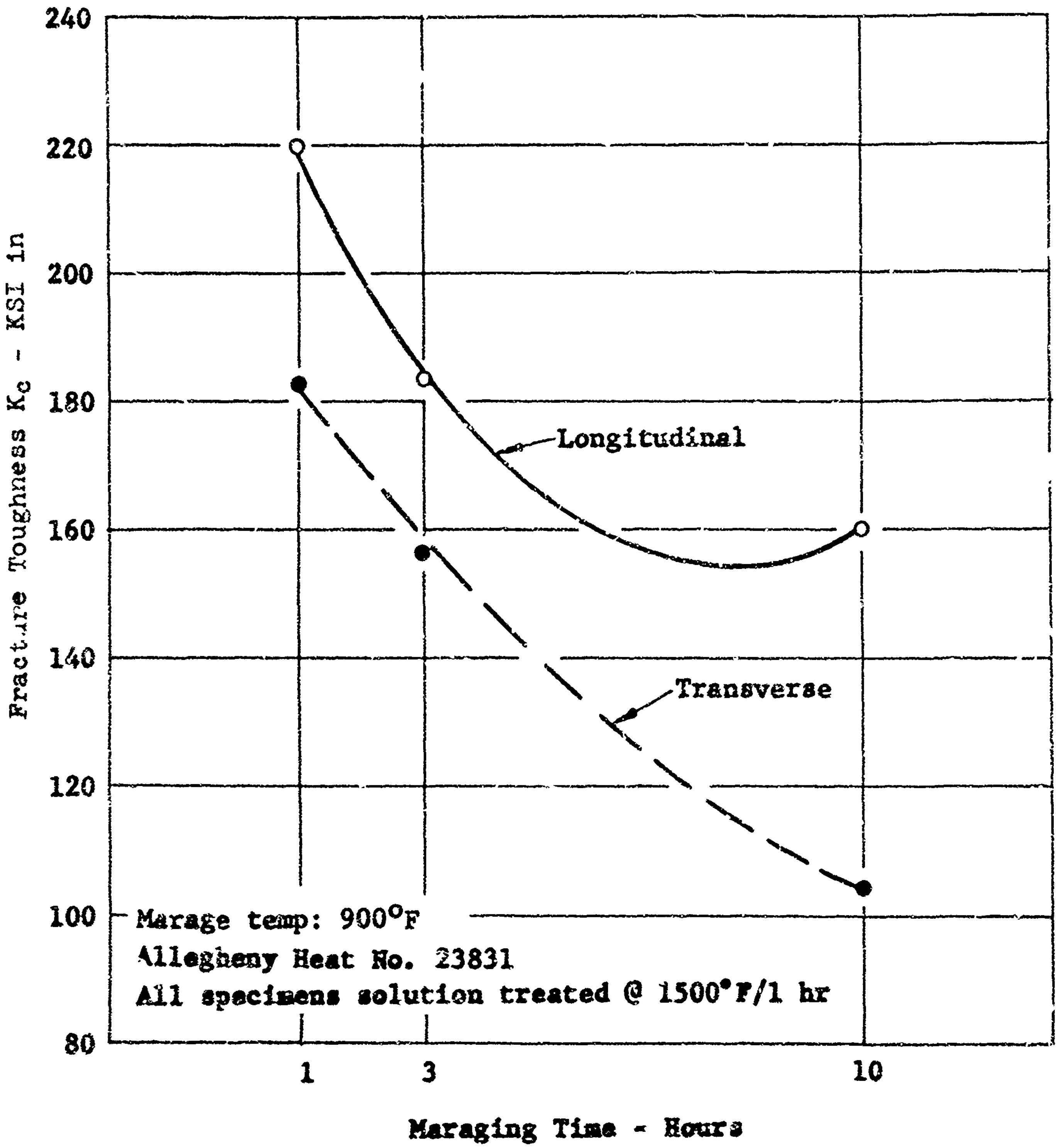


Figure 88

5347

EFFECT OF COLD WORK, MARAGING TIME,
AND MARAGING TEMPERATURE ON THE LONGITUDINAL
YIELD STRENGTH OF 18% NICKEL ALLOY (300 KSI)

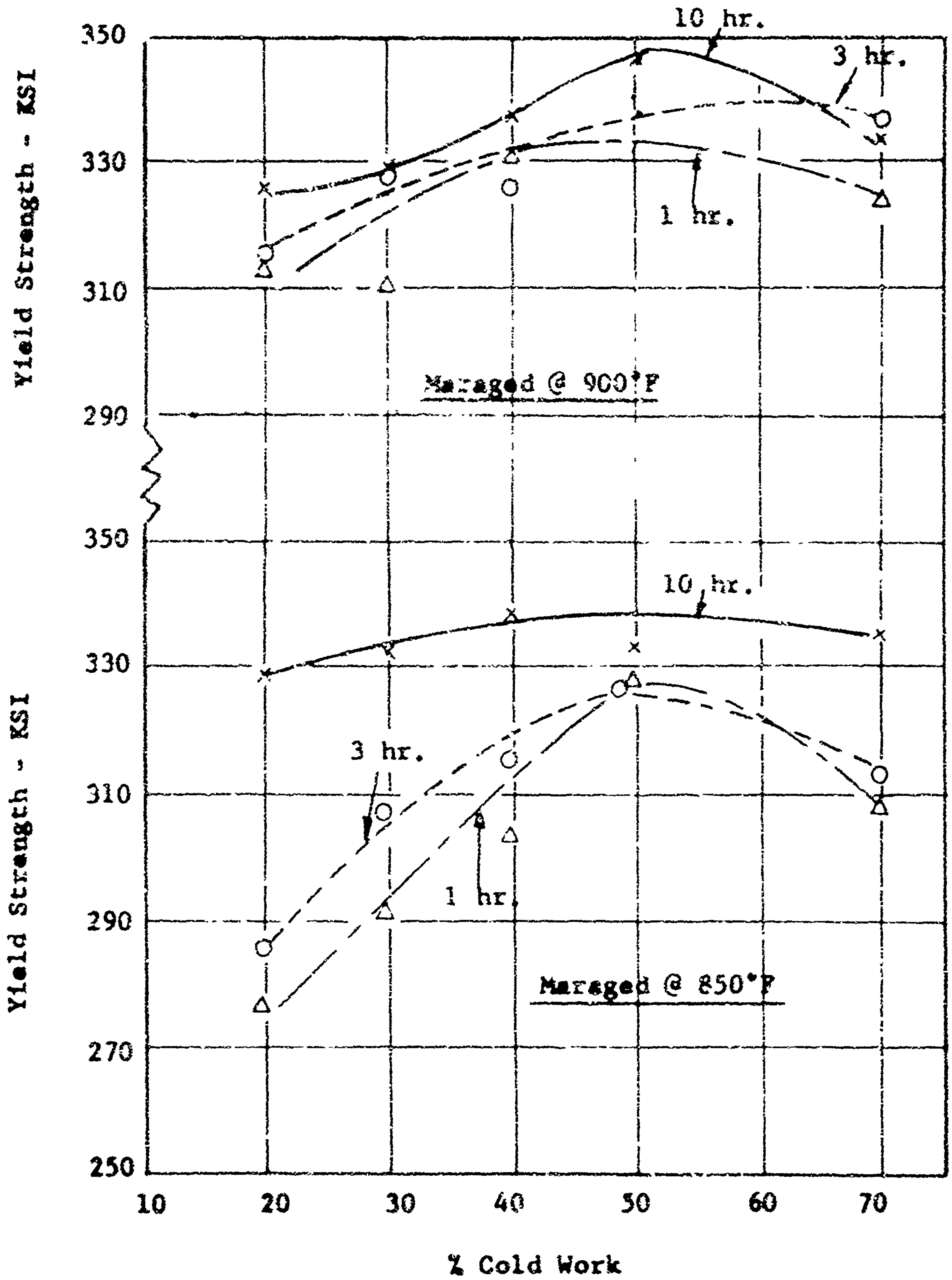


Figure 89

EFFECT OF COLD WORK, MARAGING TIME, AND MARAGING TEMPERATURE ON THE TRANSVERSE YIELD STRENGTH OF 18% NICKEL ALLOY (300 KSI)

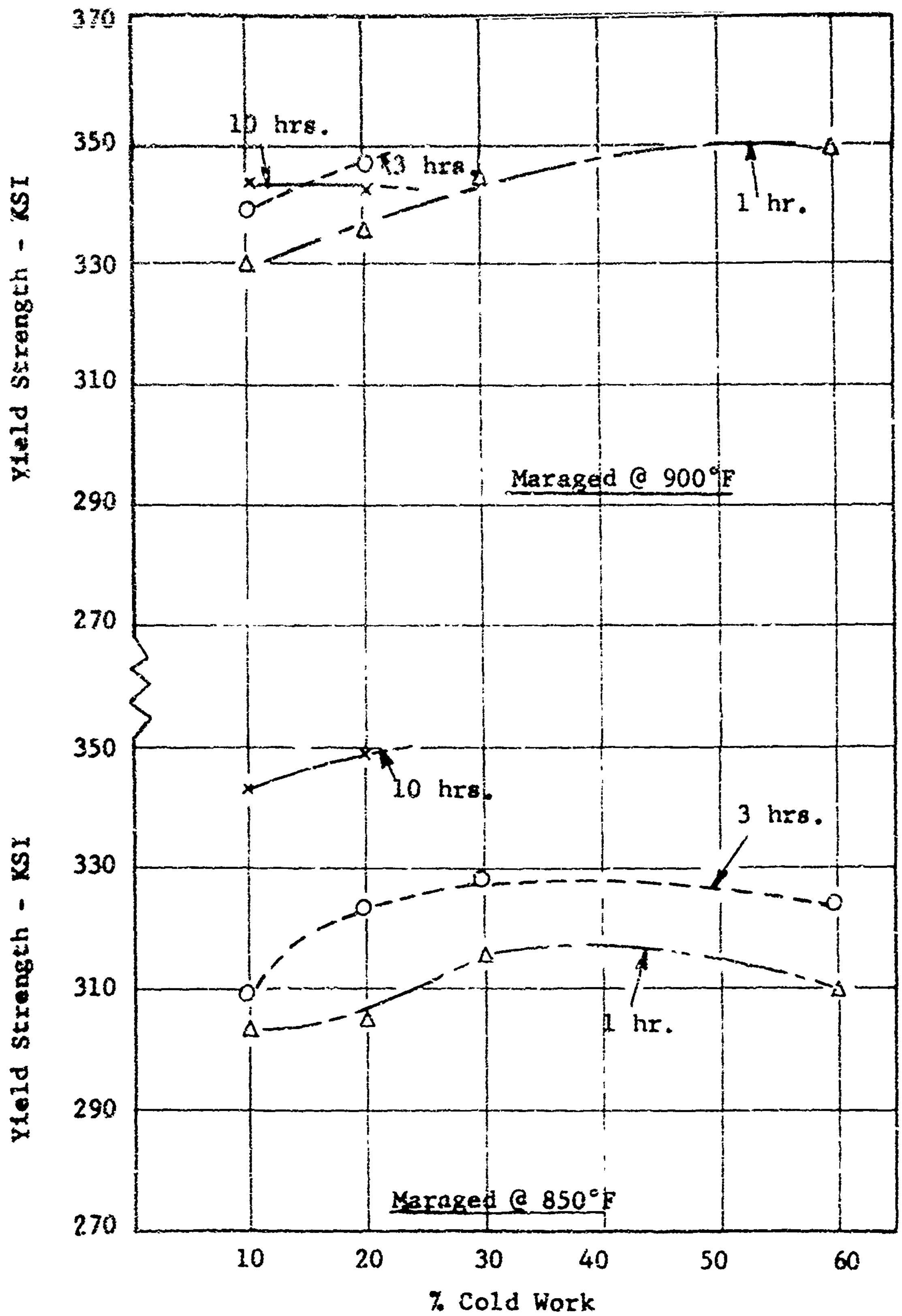


Figure 90

OPTIMIZATION OF LONGITUDINAL YIELD STRENGTH
RESPONSE OF COLD WORKED 18% NICKEL ALLOY (300KSI)

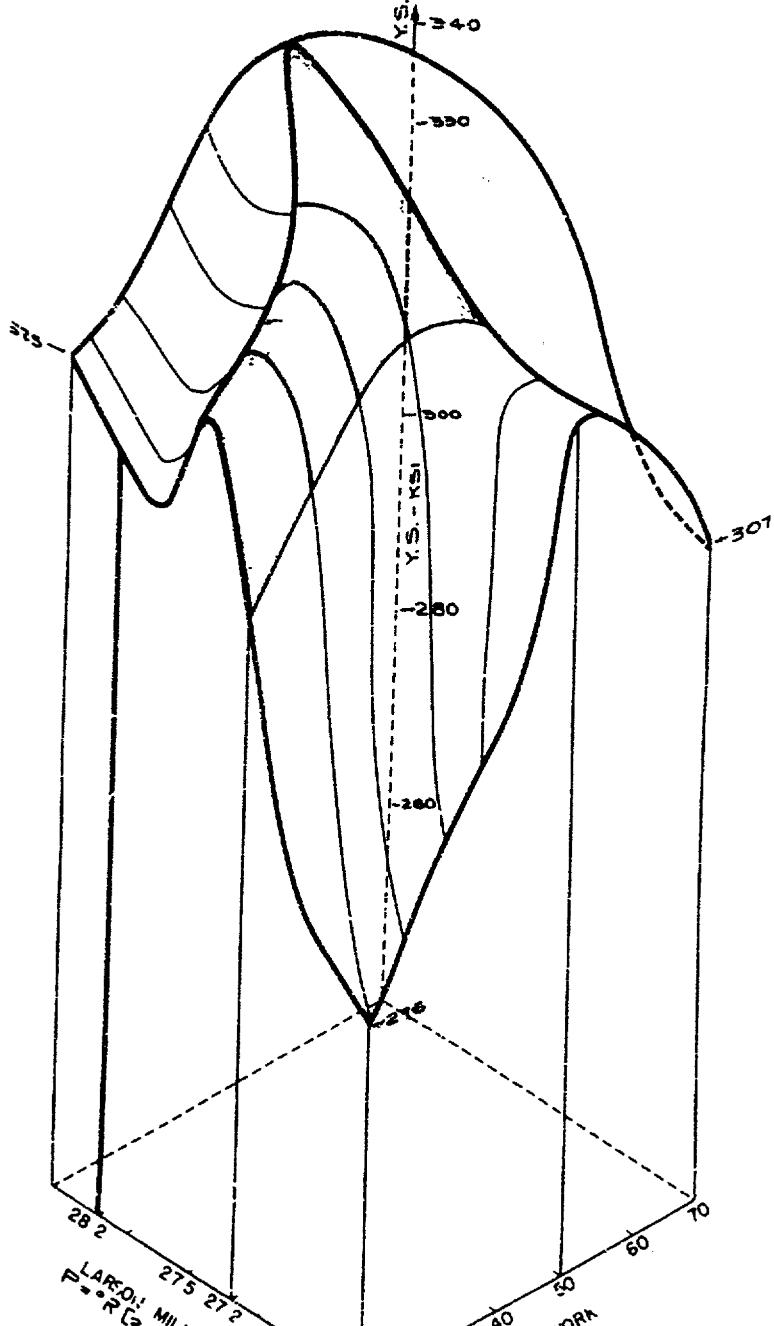


Figure 91

EFFECT OF COLD WORK AND MARAGING PARAMETERS
ON THE FRACTURE TOUGHNESS OF 18% Ni ALLOY (300 KSI)

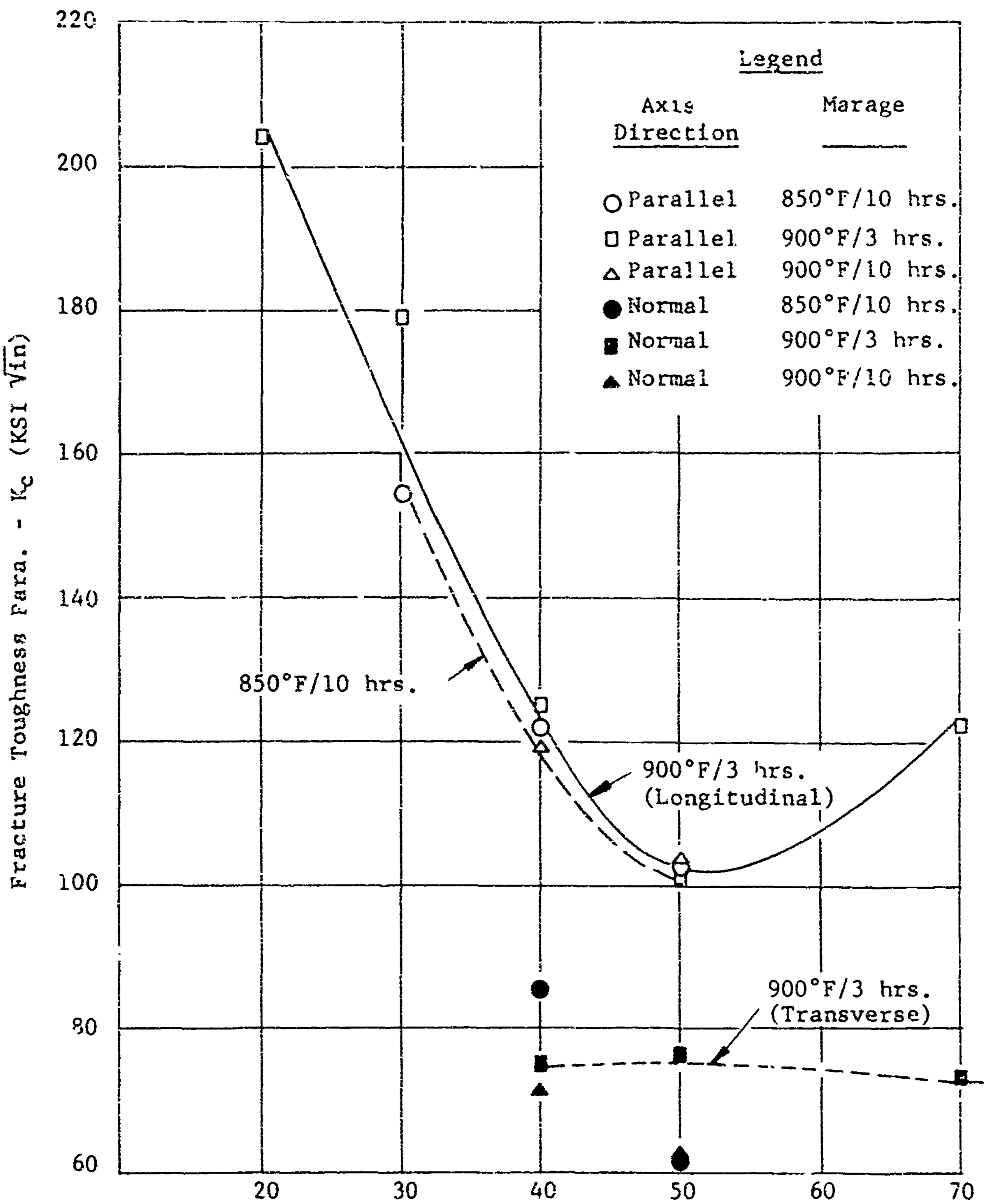


Figure 92

3877

EFFECT OF WARM WORK TEMPERATURE, MARAGING TIME, AND MARAGING TEMPERATURE ON THE LONGITUDINAL YIELD STRENGTH OF 18% NICKEL ALLOY (300 KSI)

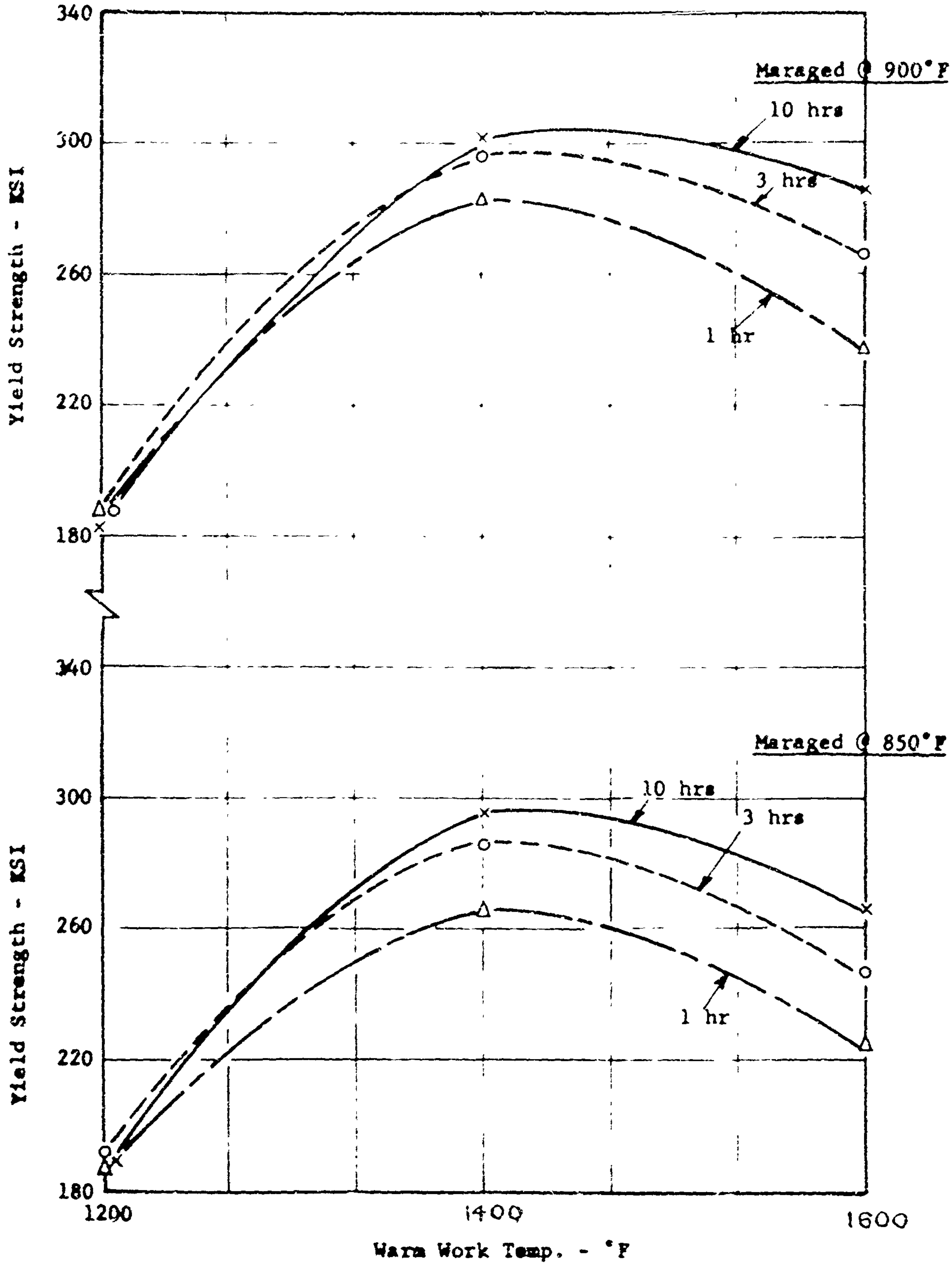


Figure 93

EFFECT OF WARM WORK TEMPERATURE, MARAGING TIME, AND MARAGING TEMPERATURE ON THE TRANSVERSE YIELD STRENGTH OF 18% NICKEL ALLOY (300 KSI)

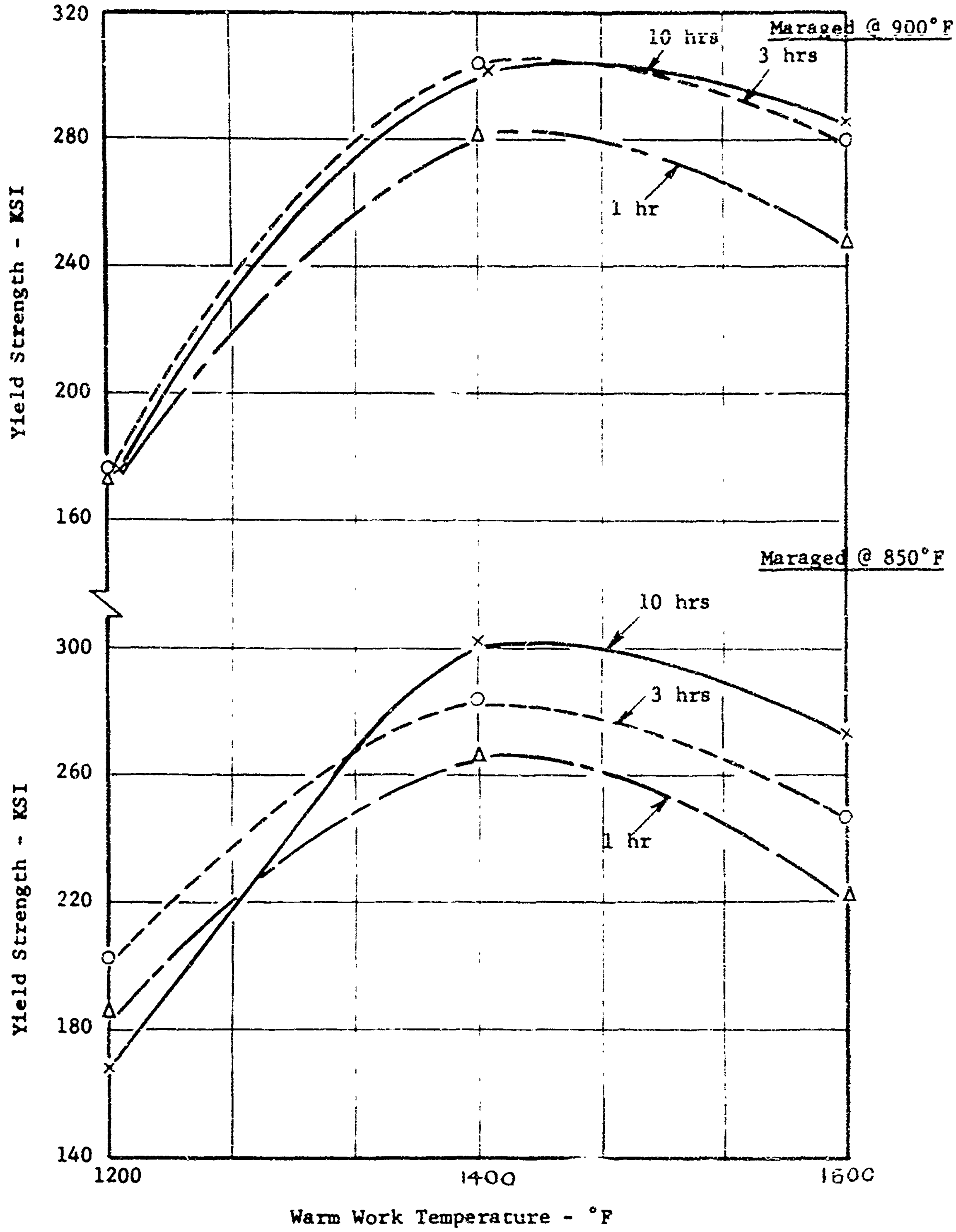


Figure 94

5350

OPTIMIZATION OF LONGITUDINAL YIELD STRENGTH RESPONSE OF WARM WORKED 18% NICKEL ALLOY (300KSI)

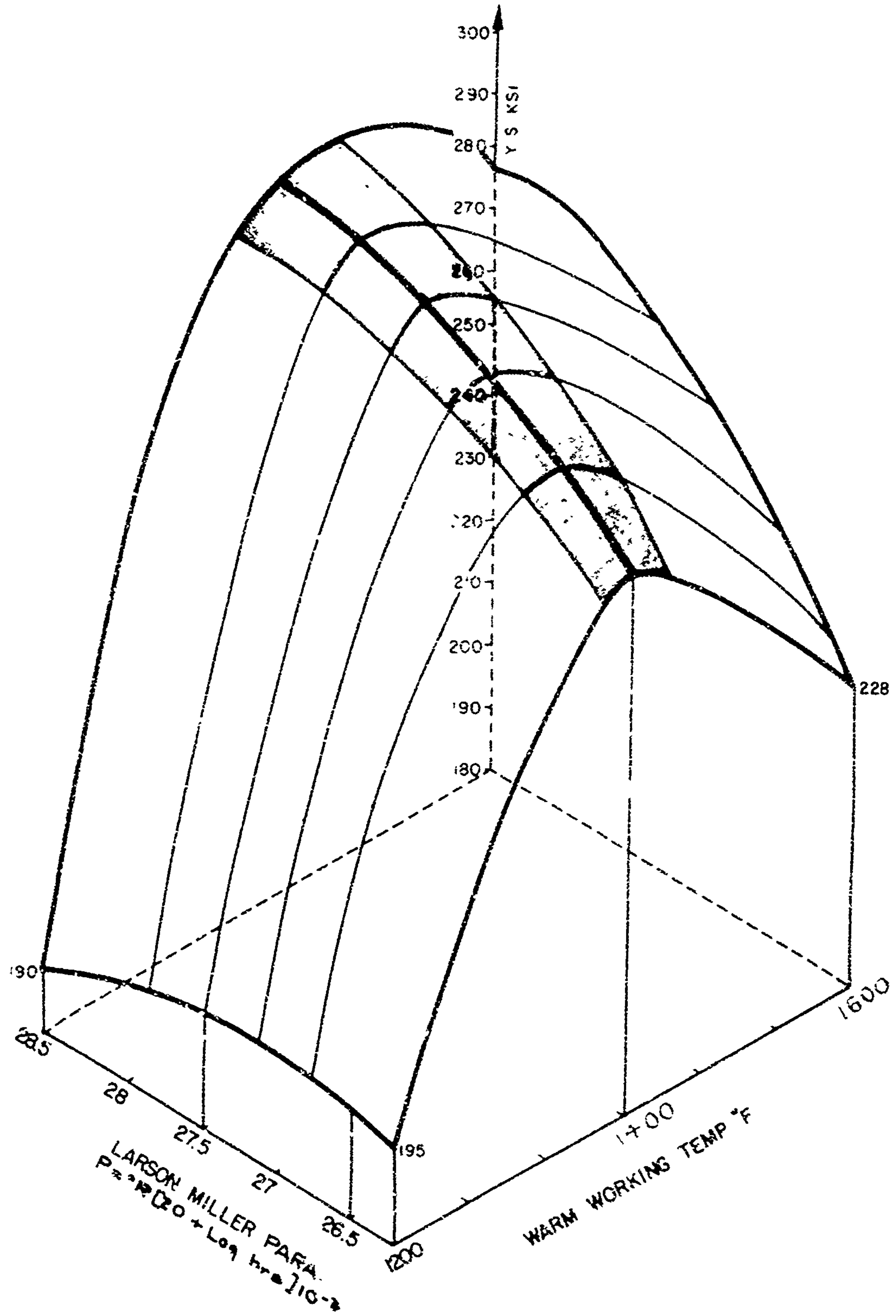


Figure 95

SHEAR SPUN 18% NICKEL CYLINDER

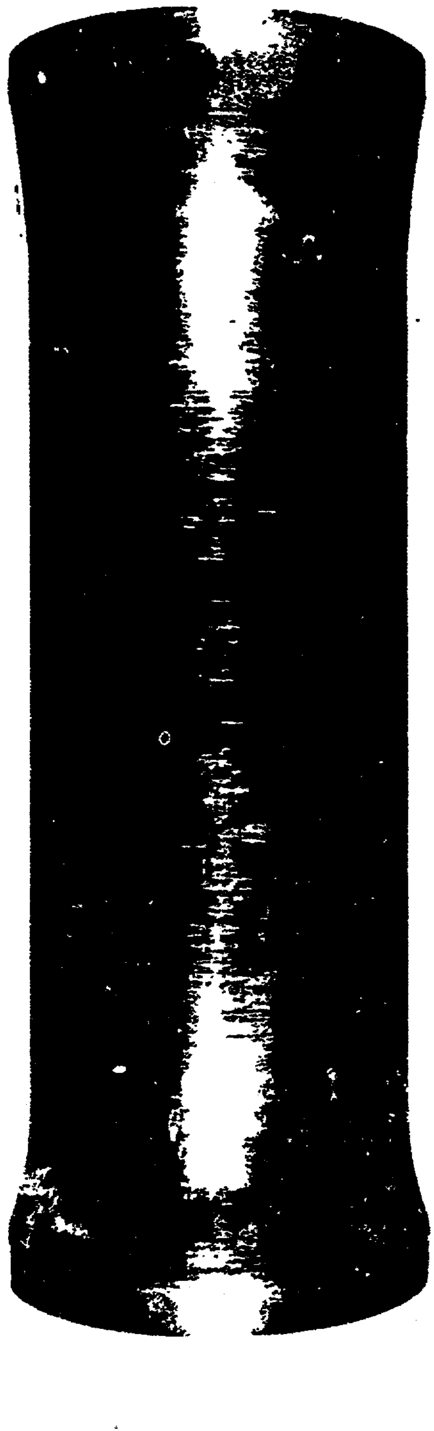


Figure 96

6" Diameter 18% Ni (300 ksi) Monolithic Cylinder which burst at 345,000 psi Section Stress

Figure 97

6" Diameter 18% Ni (300 ksi) Girth Welded Cylinder which burst at PR/T = 335 ksi
(Note undercut in weld adjacent to fracture)

Figure 98

ELEVATED TEMPERATURE TENSILE PROPERTIES OF

SOLUTION ANNEALED 18% NICKEL ALLOY (300 KSI)

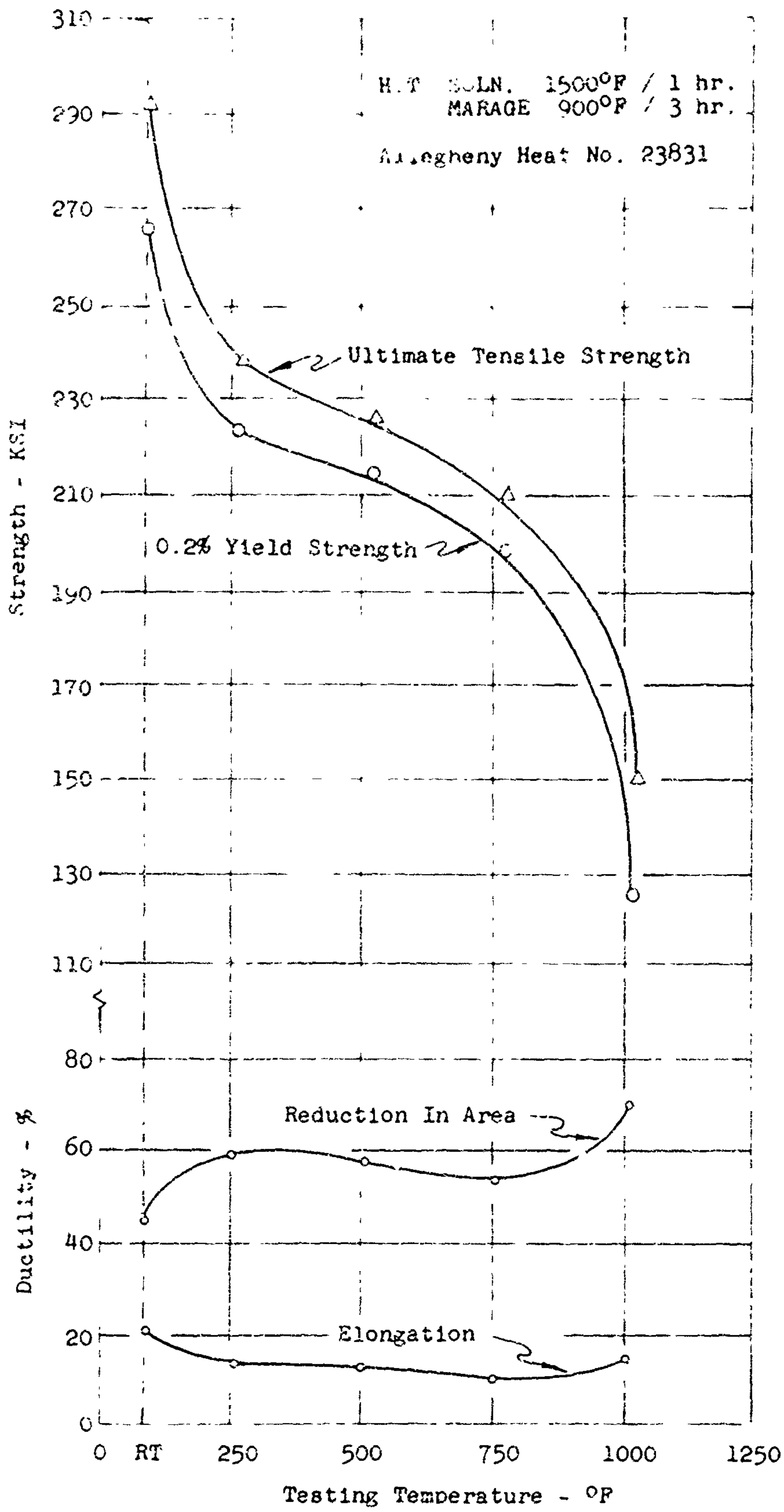


Figure 99

EFFECT OF SOLUTION TIME ON THE ELEVATED TEMPERATURE TENSILE PROPERTIES OF 18% NICKEL ALLOY (300 KSI)

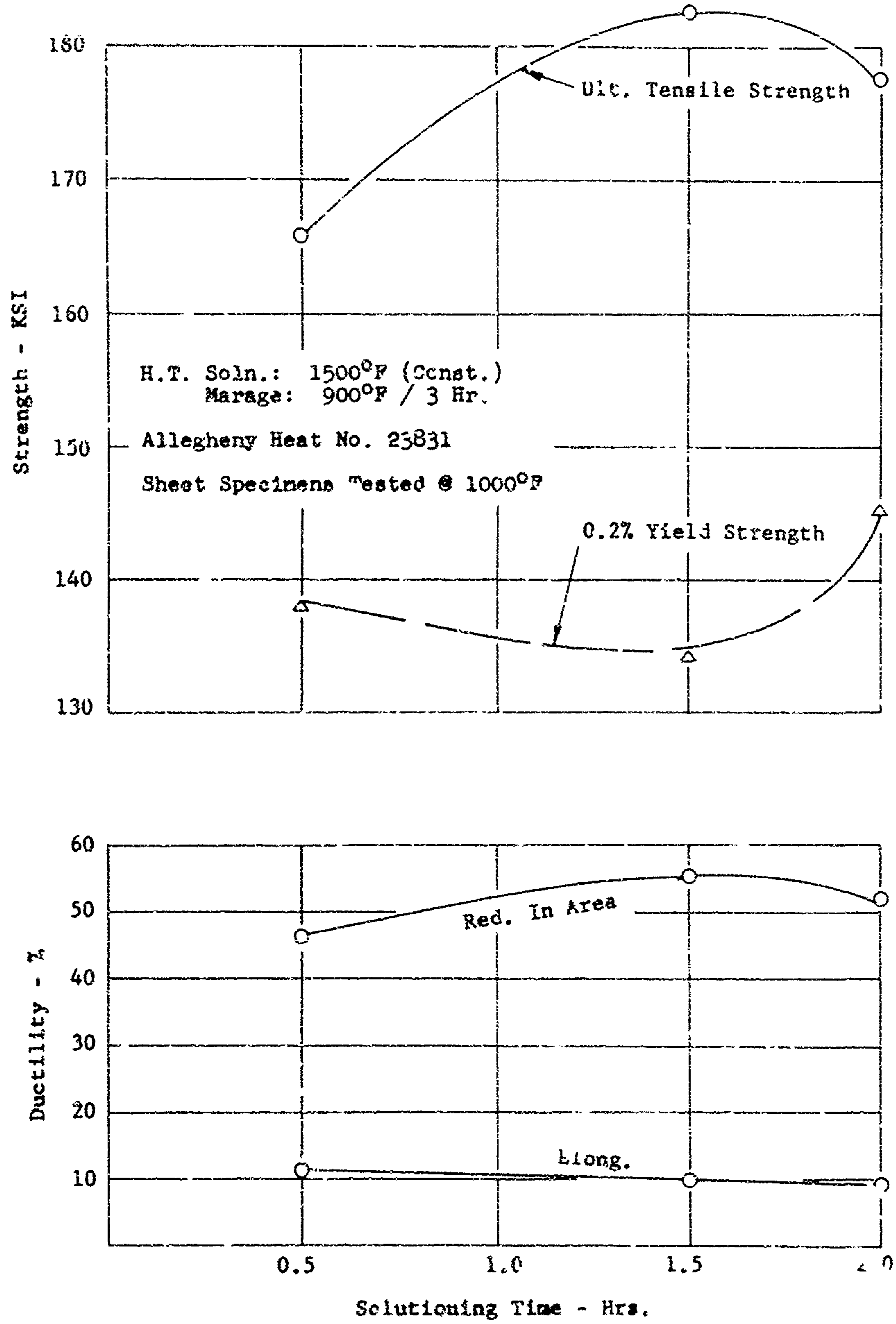
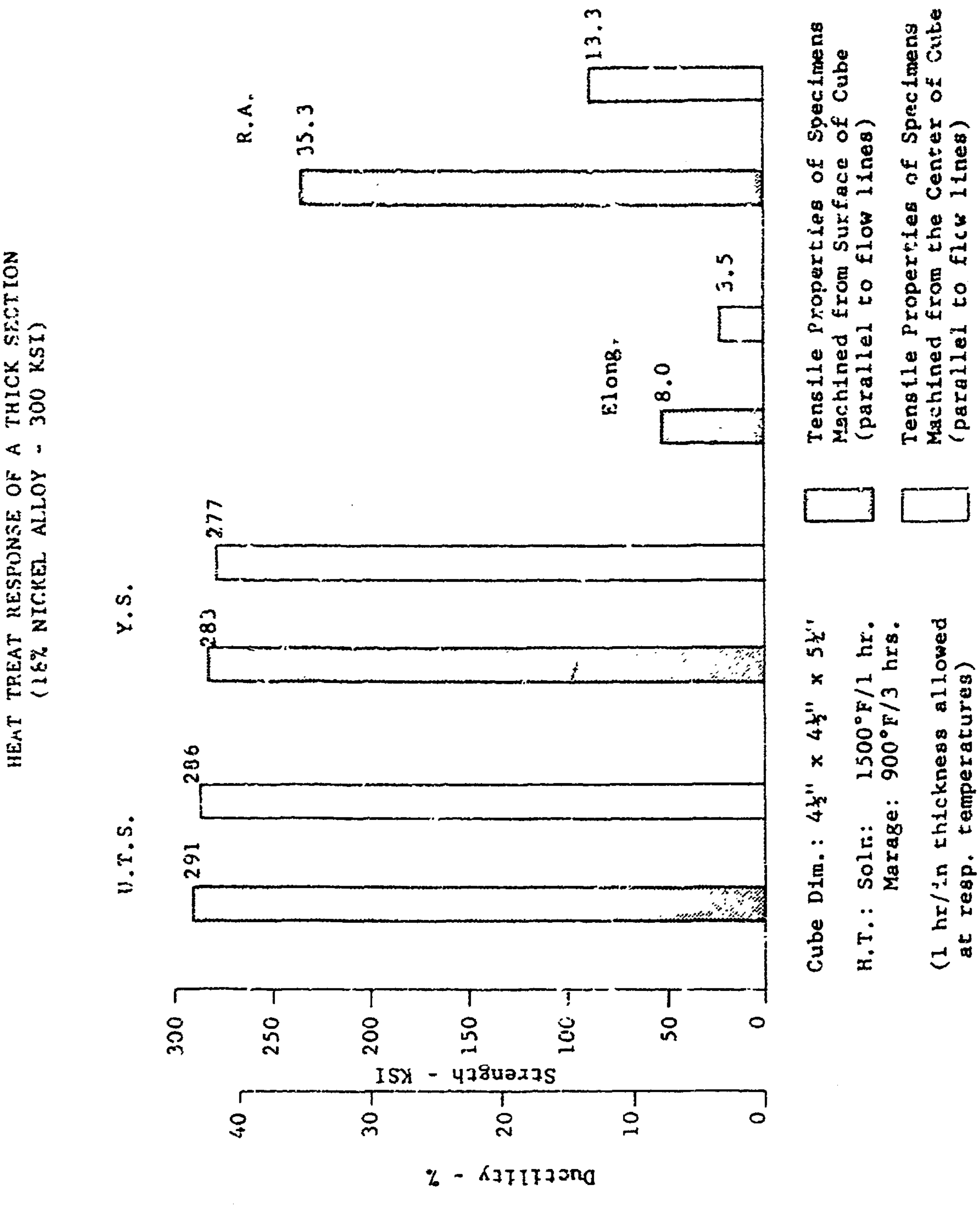


Figure 100



HEAT TREAT RESPONSE OF A THICK SECTION
(18% NICKEL ALLOY - 300 KSI)
U.T.S.
Y.S.
Elong.
R.A.
291
286
283
277
8.0
3.5
35.3
13.3
Strength - KSI
Ductility - %
300
250
200
150
100
50
0
40
30
20
10
0
Cube Dim.: 4½" x 4½" x 5½"
H.T.: Soln: 1500°F/1 hr.
Marage: 900°F/3 hrs.
(1 hr/in thickness allowed at resp. temperatures)
Allegheny Heat No. 23831
Tensile Properties of Specimens Machined from Surface of Cube (parallel to flow lines)
Tensile Properties of Specimens Machined from the Center of Cube (parallel to flow lines)

Figure 101

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 18% (300 KSI) MARAGING NICKEL STEEL

LOCATION: VERTICAL-CENTER

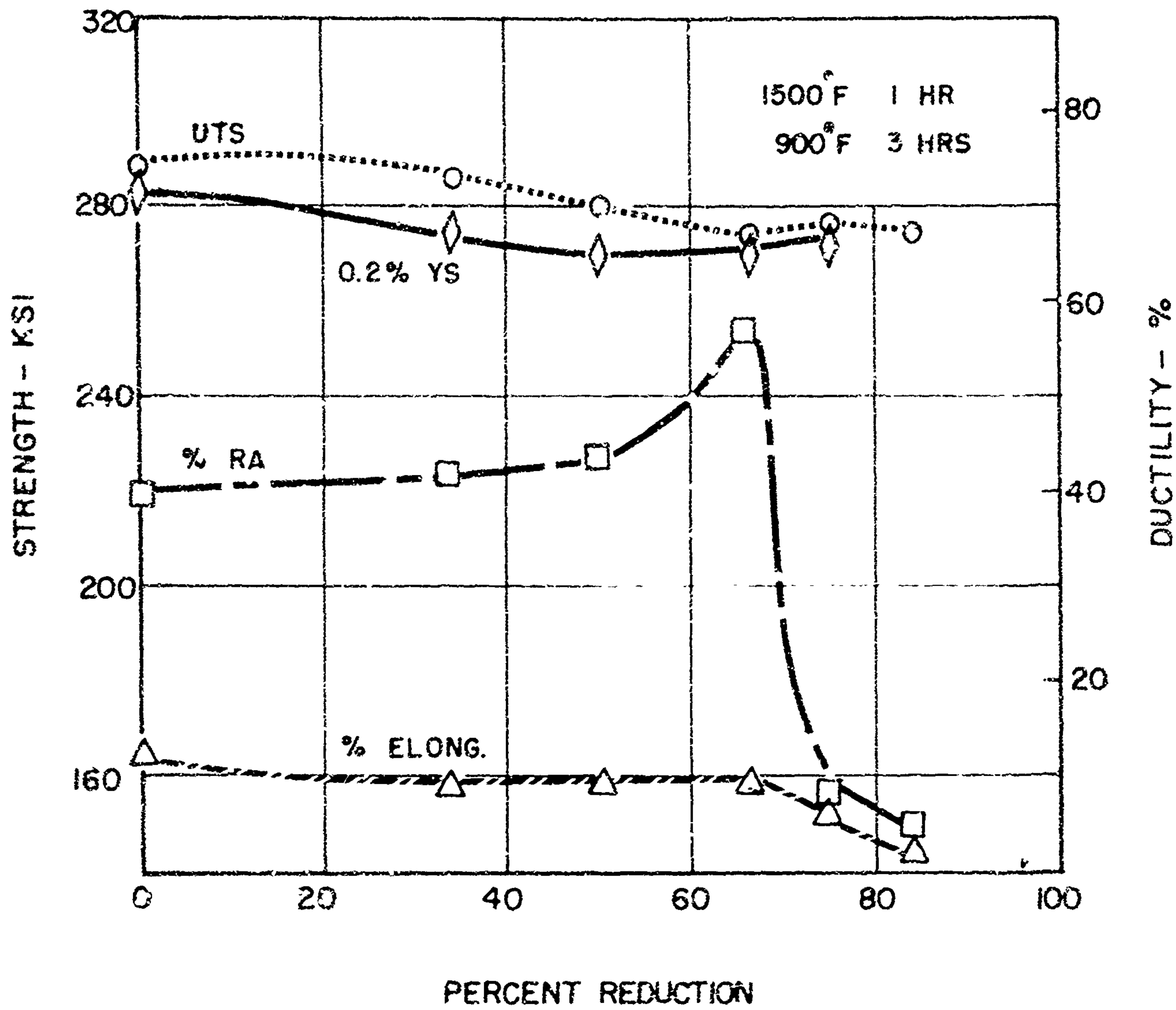


Figure 102

5339

EFFECT OF FORGING REDUCTION ON THE PROPERTIES
OF 18% (300 KSI) MARAGING NICKEL STEEL

LOCATION: VERTICAL-EDGE

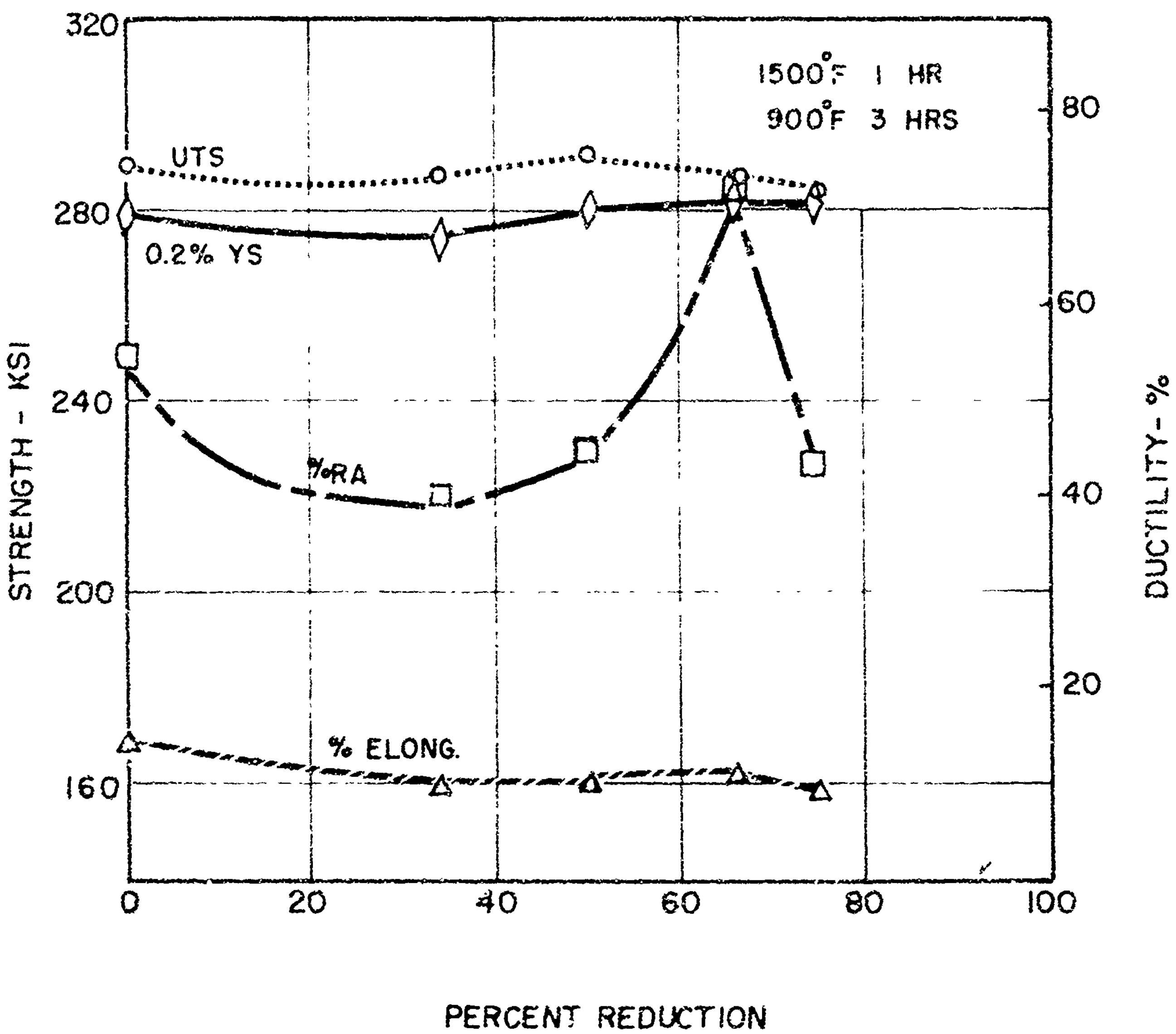


Figure 103

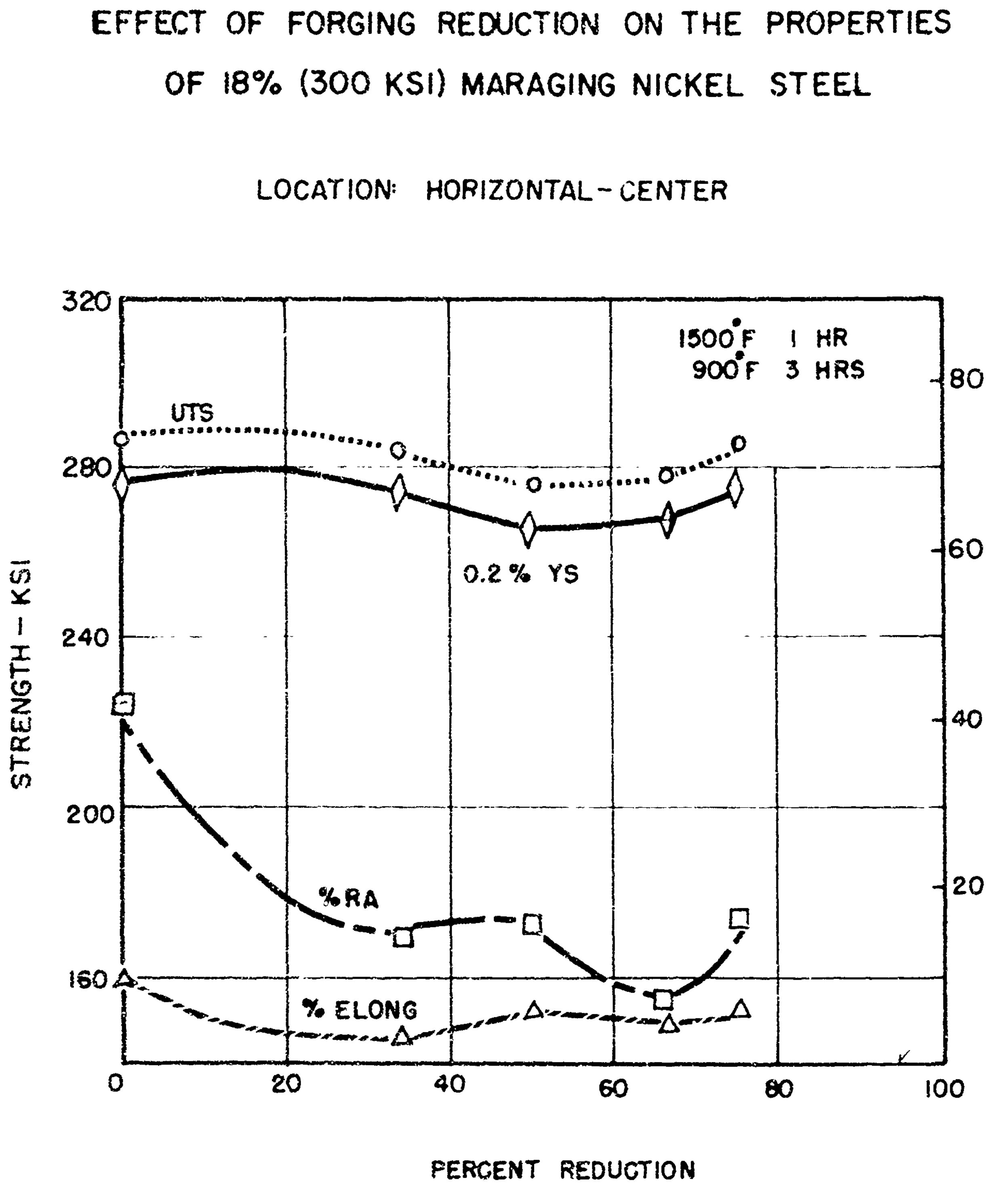

EFFECT OF FORGING REDUCTION ON THE PROPERTIES
OF 18% (300 KSI) MARAGING NICKEL STEEL
LOCATION: HORIZONTAL-CENTER
1500°F 1 HR
900°F 3 HRS
UTS
0.2% YS
%RA
% ELONG
STRENGTH – KSI
DUCTILITY – %
320
280
240
200
160
80
60
40
20
0
20
40
60
80
100
PERCENT REDUCTION

Figure 104

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 18% (300 KSI) MARAGING NICKEL STEEL

LOCATION: HORIZONTAL - EDGE

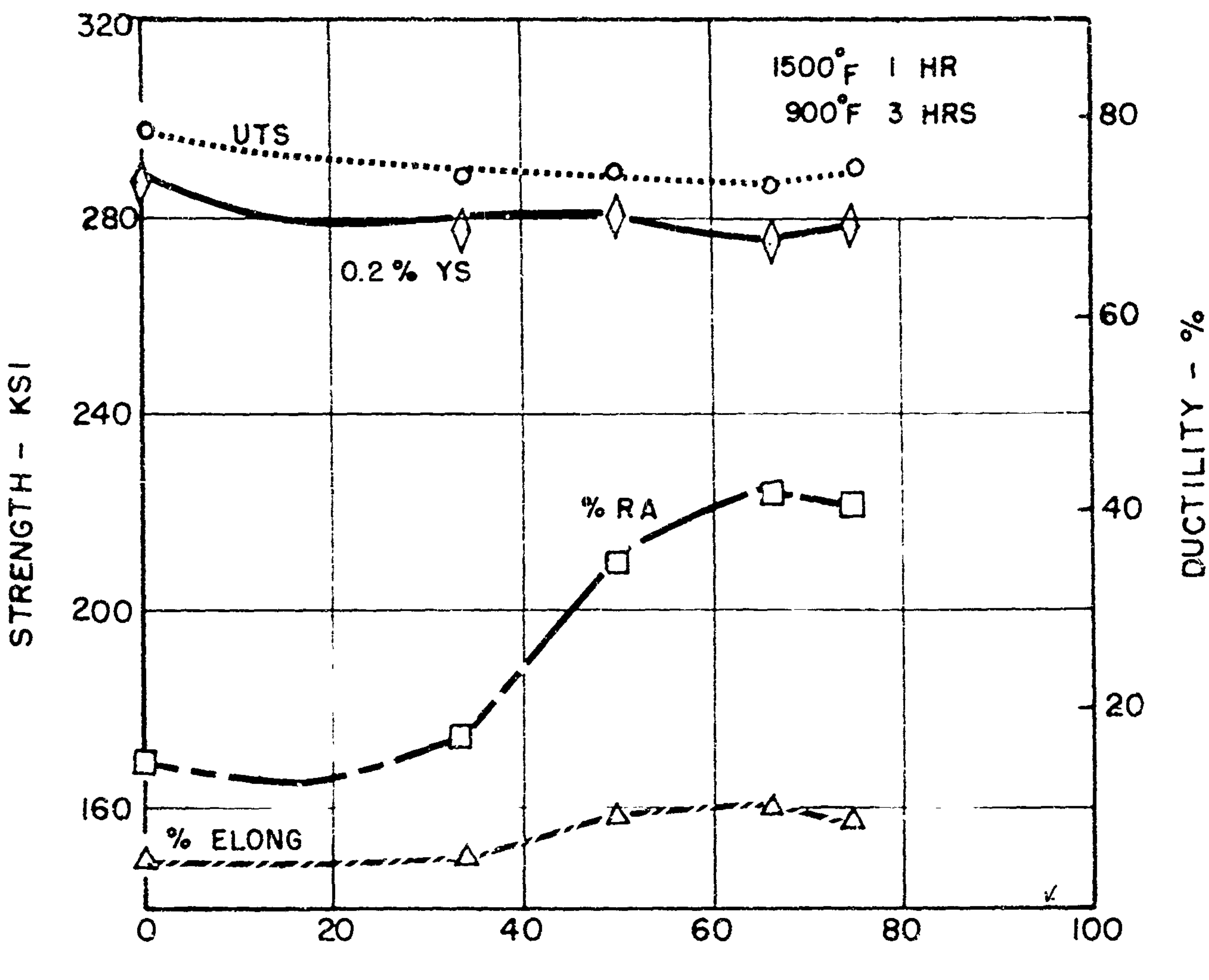
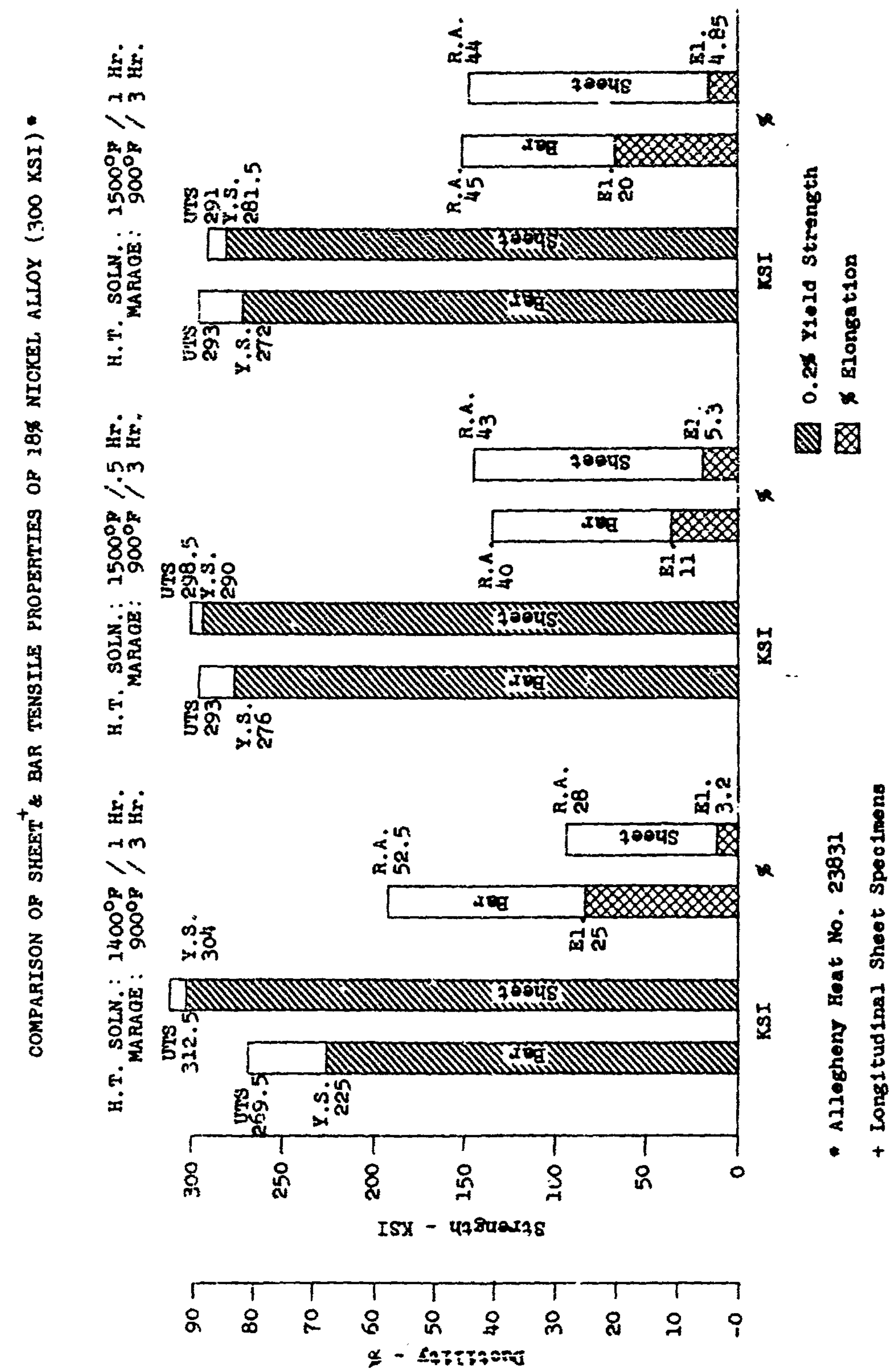


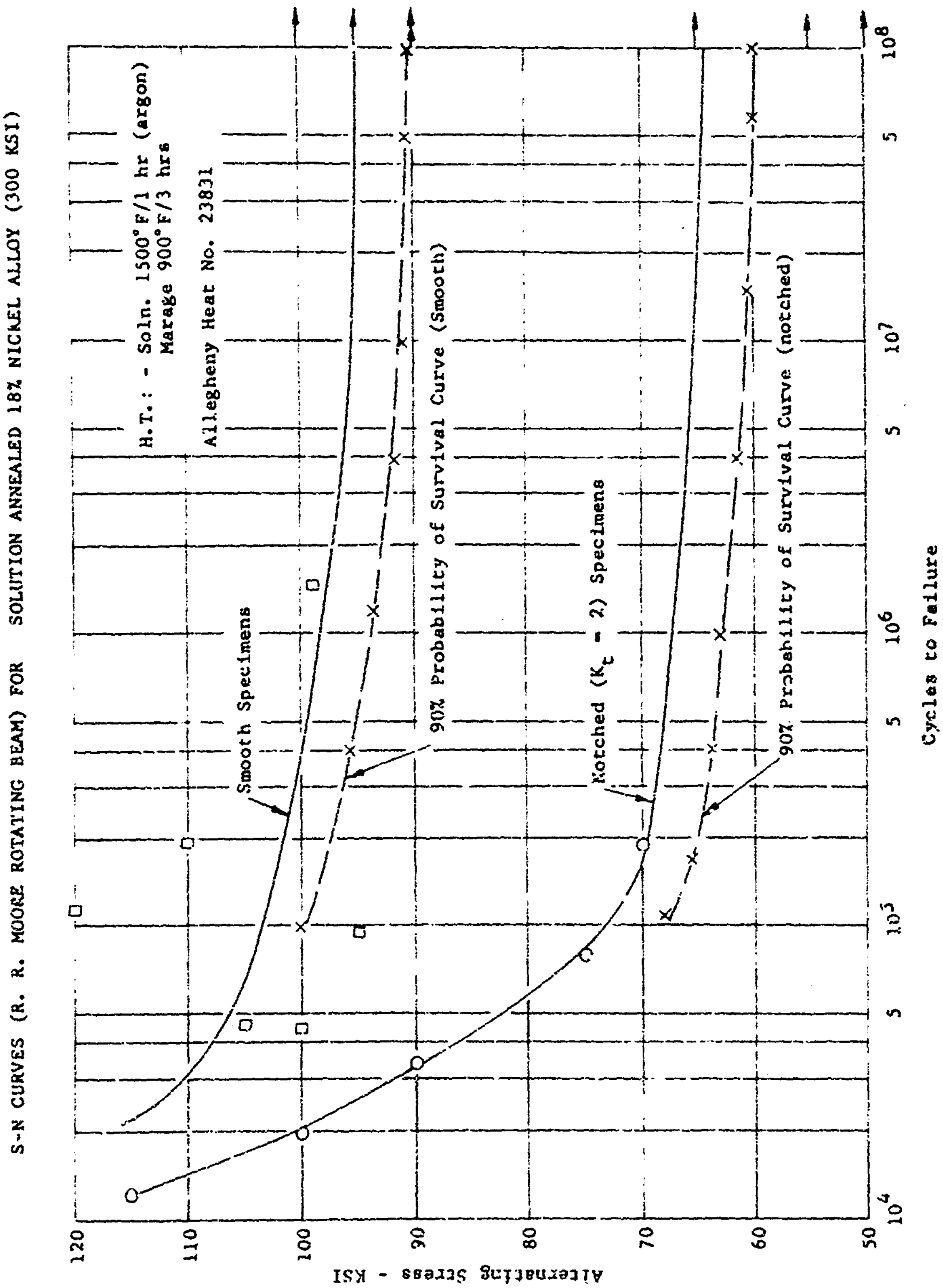
Figure 105

5337



COMPARISON OF SHEET+ & BAR TENSILE PROPERTIES OF 18% NICKEL ALLOY (300 KSI)*
H.T. SOLN.: 1400°F / 1 Hr.
MARAGE: 900°F / 3 Hr.
H.T. SOLN.: 1500°F / .5 Hr.
MARAGE: 900°F / 3 Hr.
H.T. SOLN.: 1500°F / 1 Hr.
MARAGE: 900°F / 3 Hr.
UTS 269.5
Y.S. 225
UTS 312.5
Y.S. 304
El 25
R.A. 52.5
El. 3.2
R.A. 28
UTS 293
Y.S. 276
UTS 298.5
Y.S. 290
R.A. 40
El 11
R.A. 43
El 5.3
UTS 293
Y.S. 272
UTS 291
Y.S. 281.5
R.A. 45
El 20
R.A. 44
El. 4.85
Bar
Sheet
KSI
%
Strength - KSI
Ductility - %
0.2% Yield Strength
% Elongation
* Allegheny Heat No. 23831
+ Longitudinal Sheet Specimens

Figure 106



S-N CURVES (R. R. MOORE ROTATING BEAM) FOR SOLUTION ANNEALED 18% NICKEL ALLOY (300 KSI)
H.T.: - Soln. 1500°F/1 hr (argon)
Marage 900°F/3 hrs
Allegheny Heat No. 23831
Smooth Specimens
90% Probability of Survival Curve (Smooth)
Notched (K_t = 2) Specimens
90% Probability of Survival Curve (notched)
Alternating Stress - KSI
120
110
100
90
80
70
60
50
10^4
5
10^5
5
10^6
5
10^7
5
10^8
Cycles to Failure

Figure 107

CHARPY IMPACT STRENGTH OF SOLUTION ANNEALED

18% NICKEL ALLOY (300 KSI)

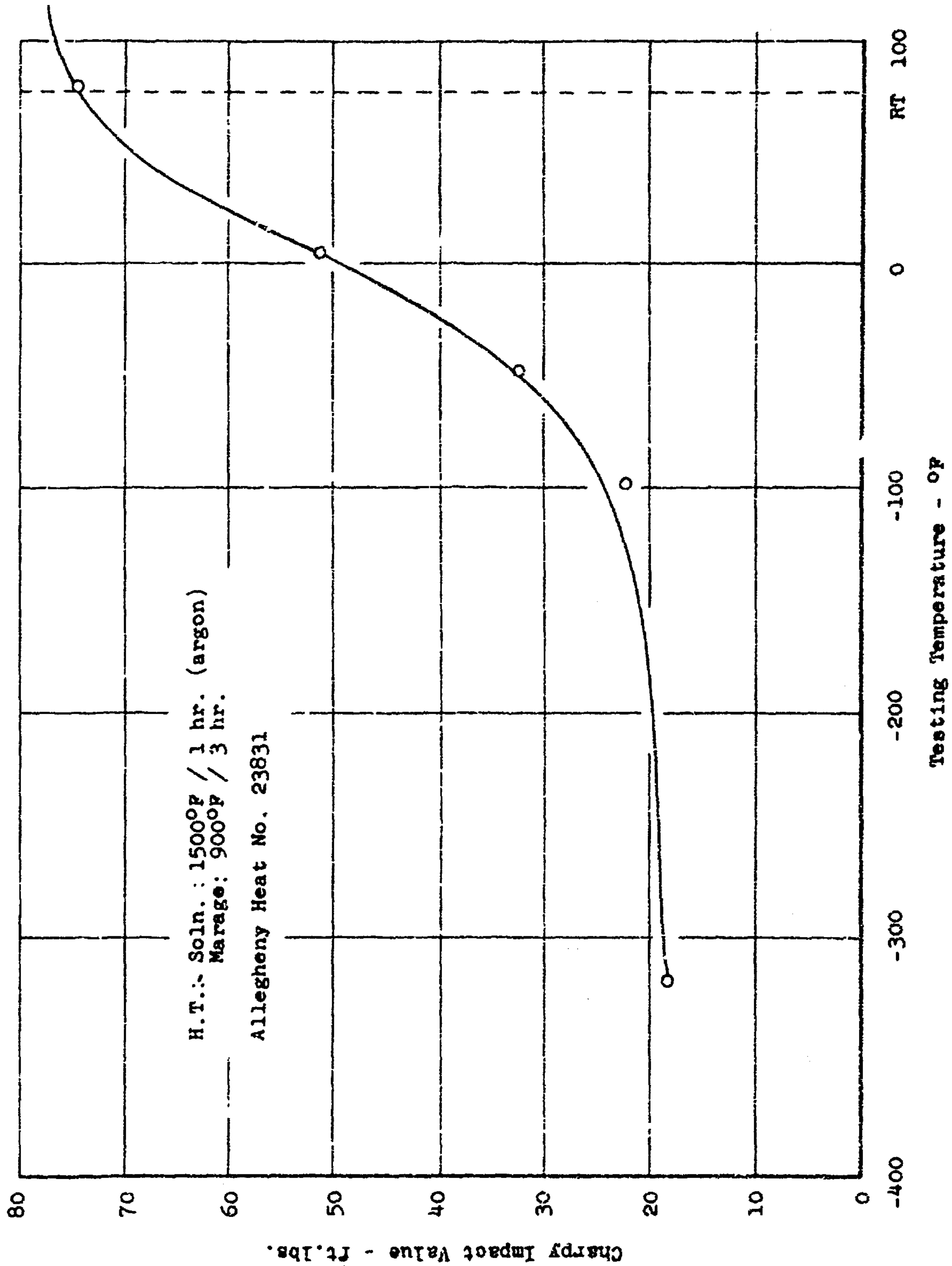
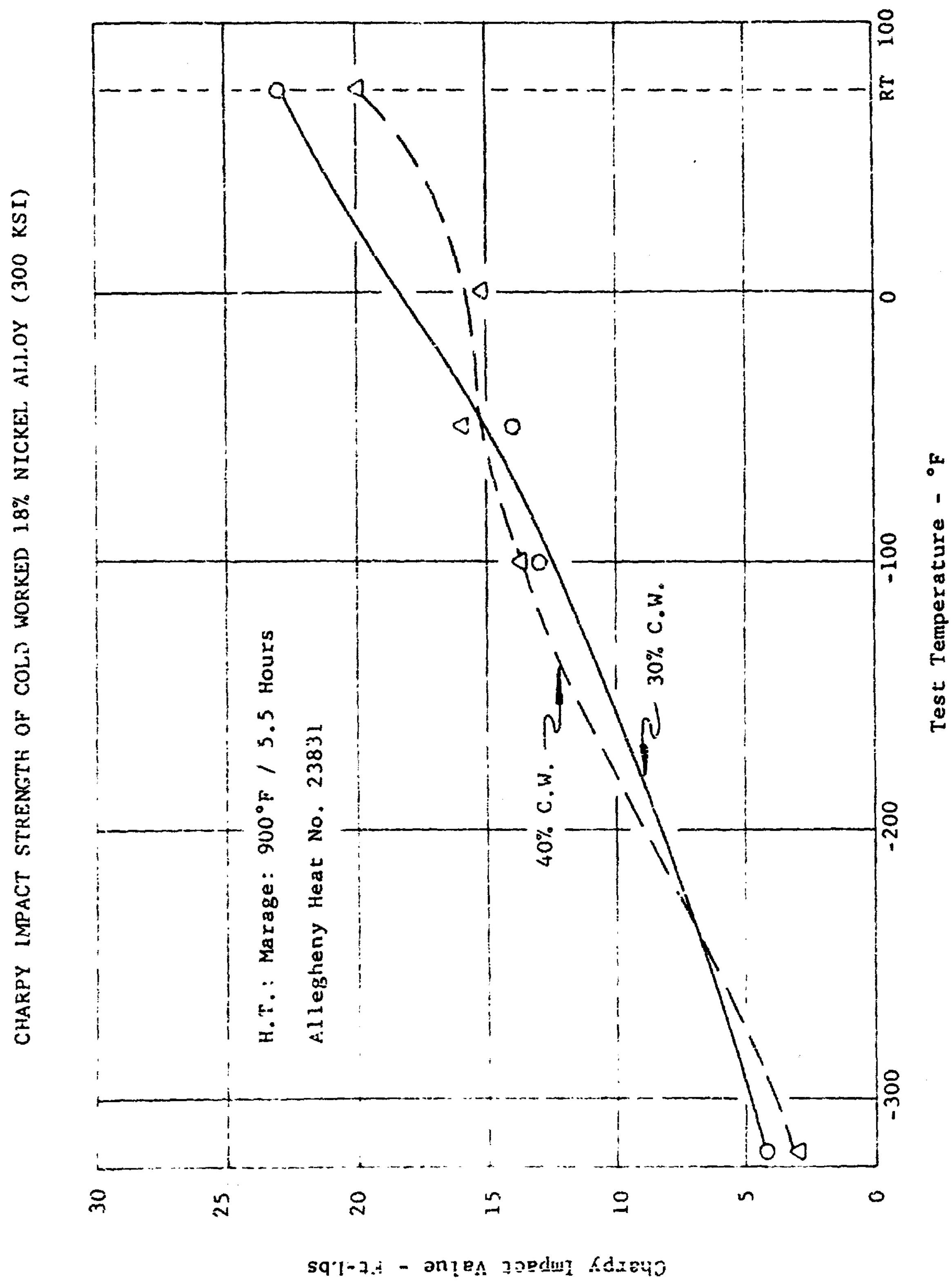


Figure 108



CHARPY IMPACT STRENGTH OF COLD WORKED 18% NICKEL ALLOY (300 KSI)
H.T.: Marage: 900°F / 5.5 Hours
Allegheny Heat No. 23831
40% C.W.
30% C.W.
Charpy Impact Value - Ft-lbs
Test Temperature - °F
RT
100
0
-100
-200
-300
30
25
20
15
10
5
0

Figure 109

COMPARISON OF FRACTURE TOUGHNESS OF 18% NICKEL ALLOY (300 KSI)
IN VARIOUS CONDITIONS

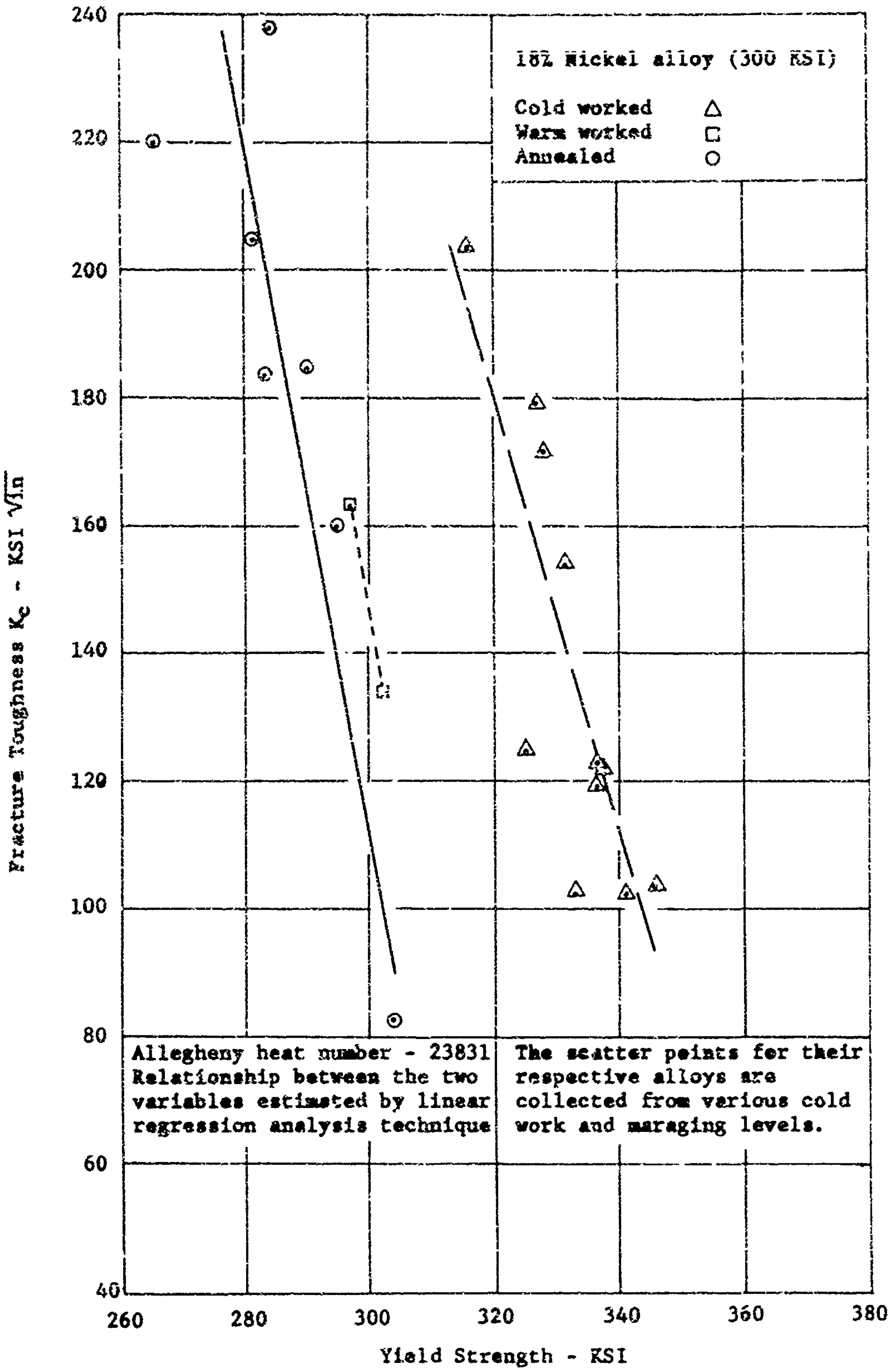
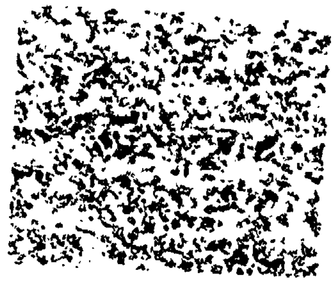


Figure 110

5360

MICROSTRUCTURE OF SOLUTION TREATED 18% NICKEL (300 KSI) ALLOY

Solutioned 1500°F/1 hr.



Mag. 500 X

Etchant: Marble's + Modified Fry's

Solutioned 1500°F/1 hr.

Mag. 18000 X

Two Stage Carbon Replica

Solutioned 1800°F/1 hr.

Mag. 500 X

Etchant: Marble's + Modified Fry's

Solutioned 1800°F/1 hr.

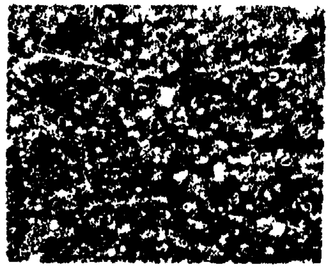
Mag. 18000 X

Two Stage Carbon Replica

Figure 111

MICROSTRUCTURE OF SOLUTIONED AND MARAGED, AND COLD WORK AND MARAGED 18% NICKEL (300 KSI) ALLOY

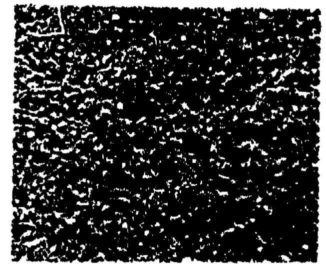
Solutioned 1500°F/1 hr.
Maraged 900°F/10 hrs.



Mag. 500 X

Etchant: Marble's + Modified Fry's

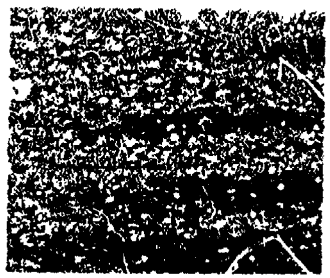
Solutioned 1500°F/1 hr.
Maraged 900°F/10 hrs.



Mag. 18000 X

Two Stage Carbon Replica

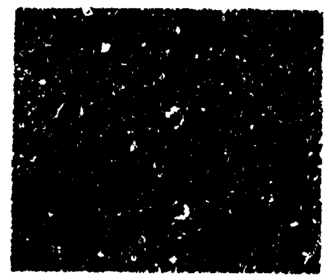
Cold Worked 30%,
Maraged 900°F/5.4 hrs.



Mag. 500 X

Etchant: Marble's + Modified Fry's

Cold Worked 30%,
Maraged 900°F/5.4 hrs.



Mag. 18000 X

Two Stage Carbon Replica

Figure 112

18% NICKEL ALLOY (300 KSI) WELD HARDNESS
DATA VERTICAL TRAVERSE ALONG WELD CENTERLINE

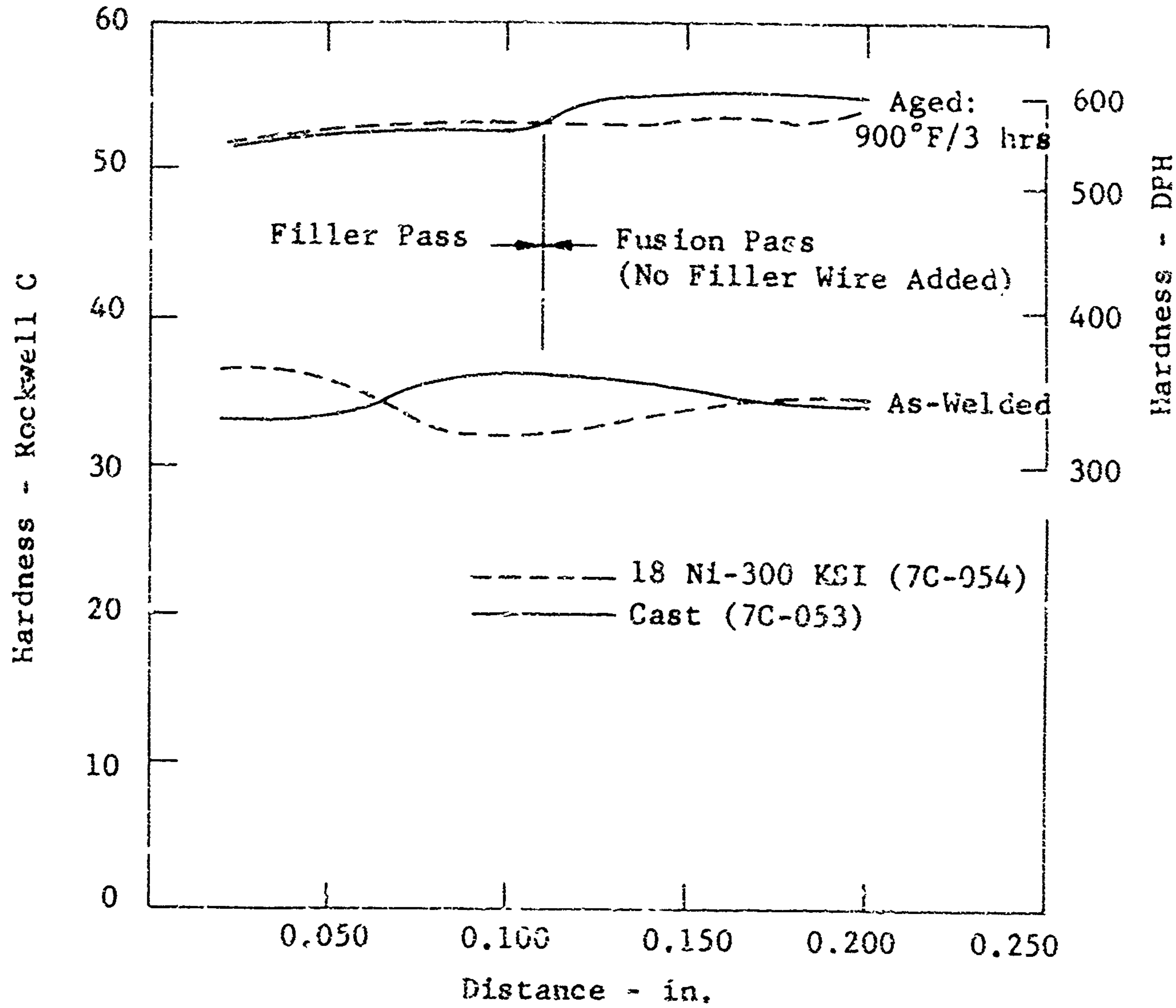


Figure 113

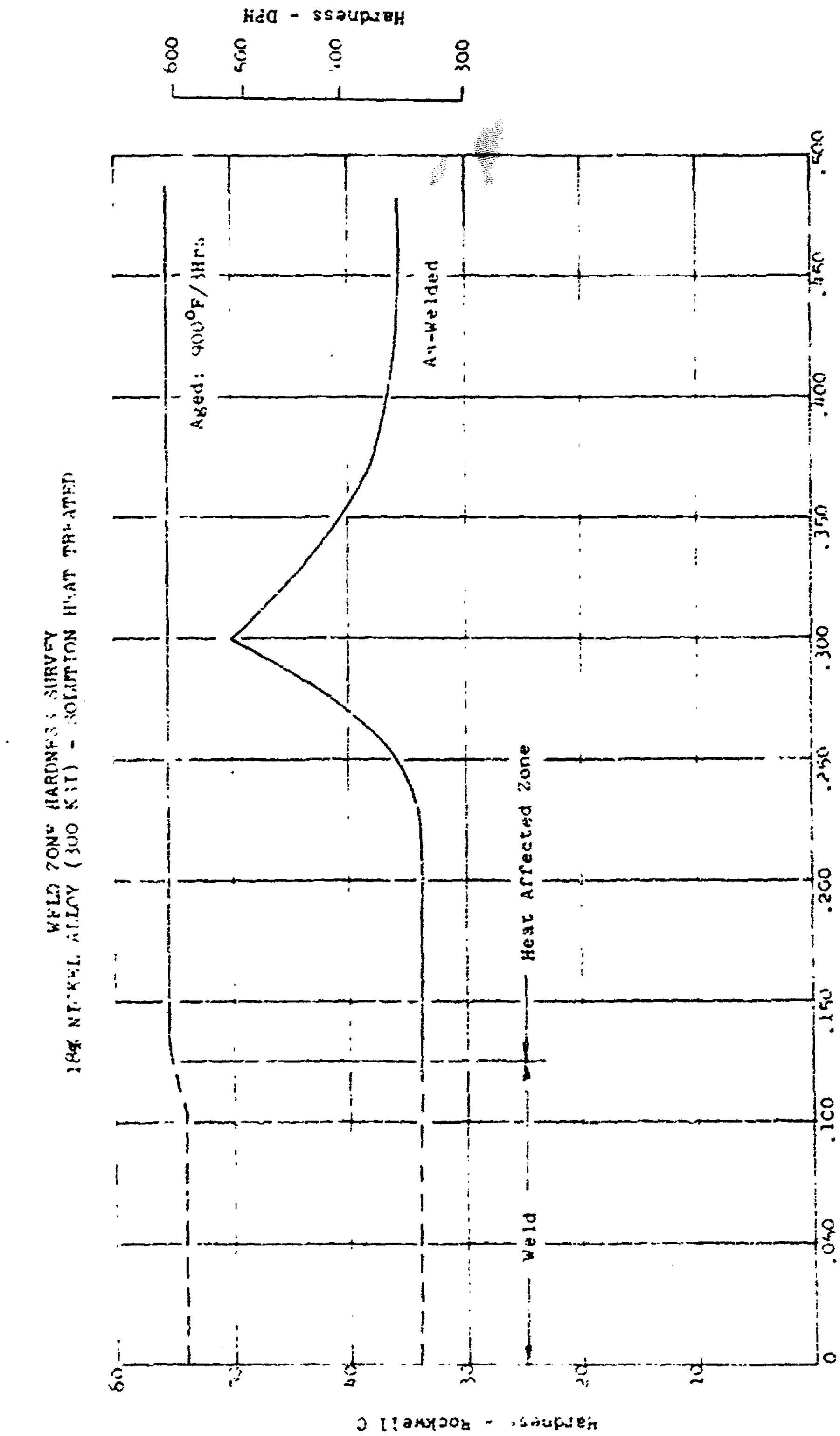

WELD ZONE HARDNESS SURVEY
18% NICKEL ALLOY (300 KSI) - SOLUTION HEAT TREATED
Hardness - DPH
Hardness - Rockwell C
Aged: 900°F/3Hrs
As-Welded
Heat Affected Zone
Weld

Figure 114

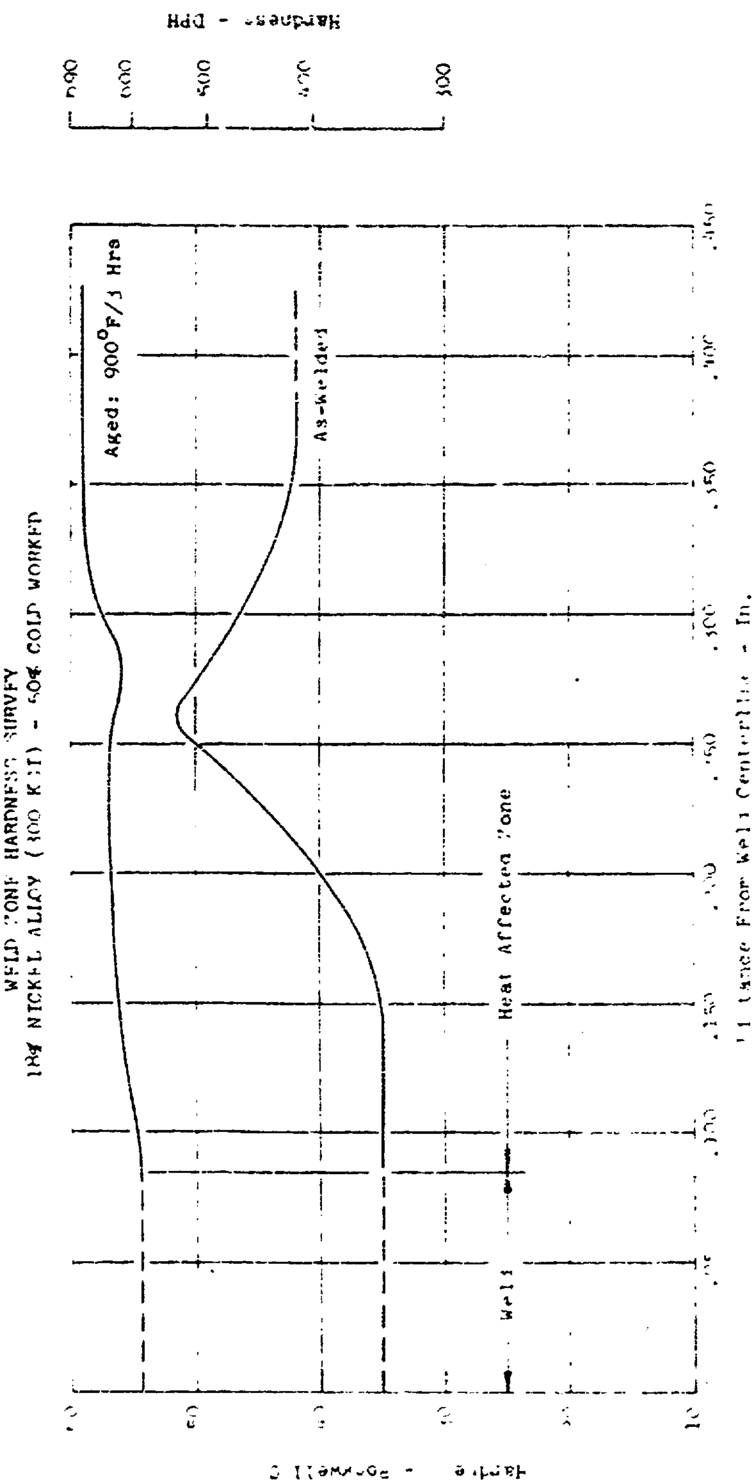

WELD ZONE HARDNESS SURVEY
COLD WORKED
Aged: 900°F/3 Hrs
As-Welded
Heat Affected Zone
Hardness - DPH

Figure 115

COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE PROPERTIES
18% NICKEL ALLOY (300 KSI) - SOLUTION HEAT TREATED SHEET

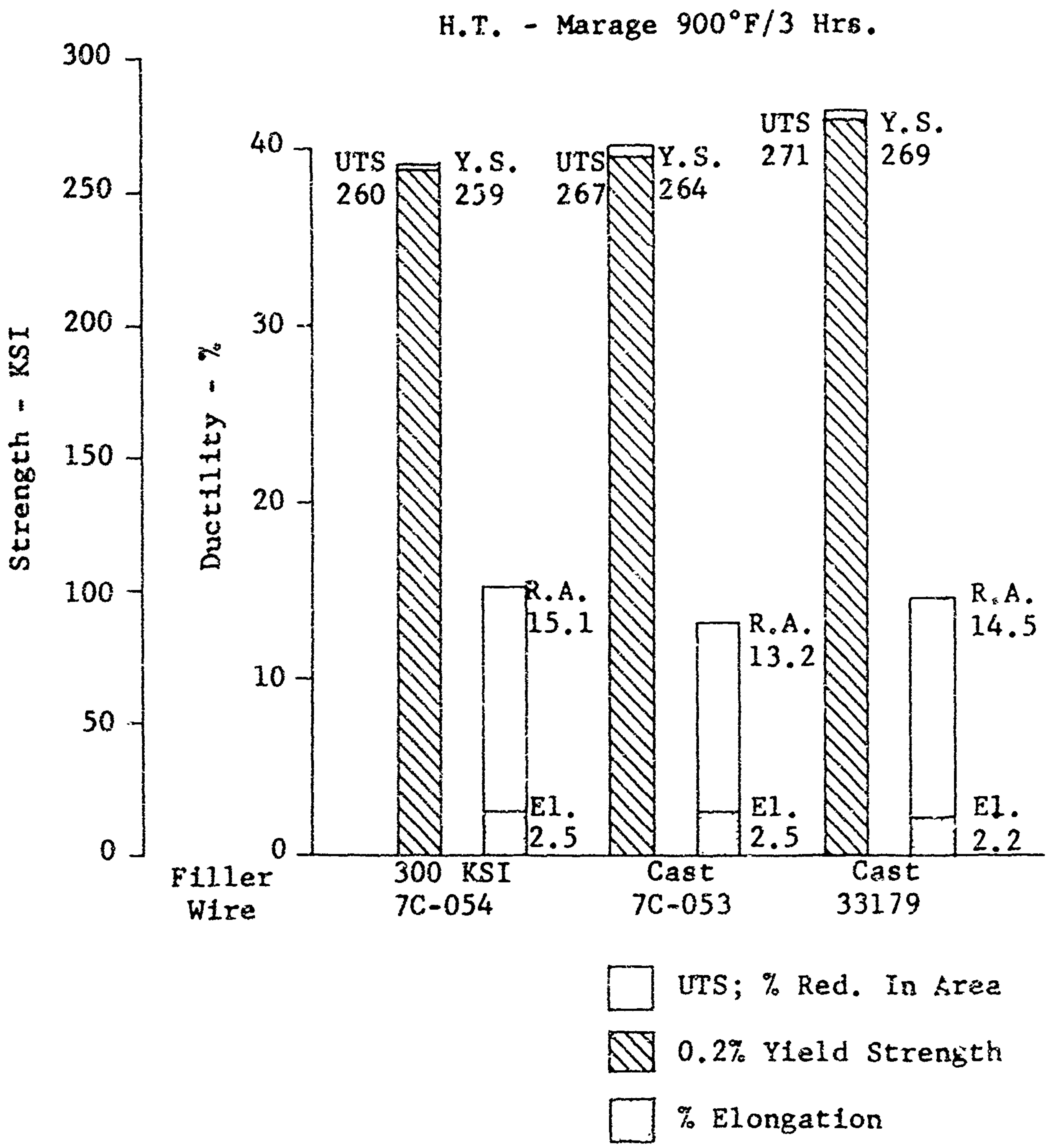


Figure 116

COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE PROPERTIES
18% NICKEL ALLOY (300 KSI) - 50% COLD WORKED SHEET

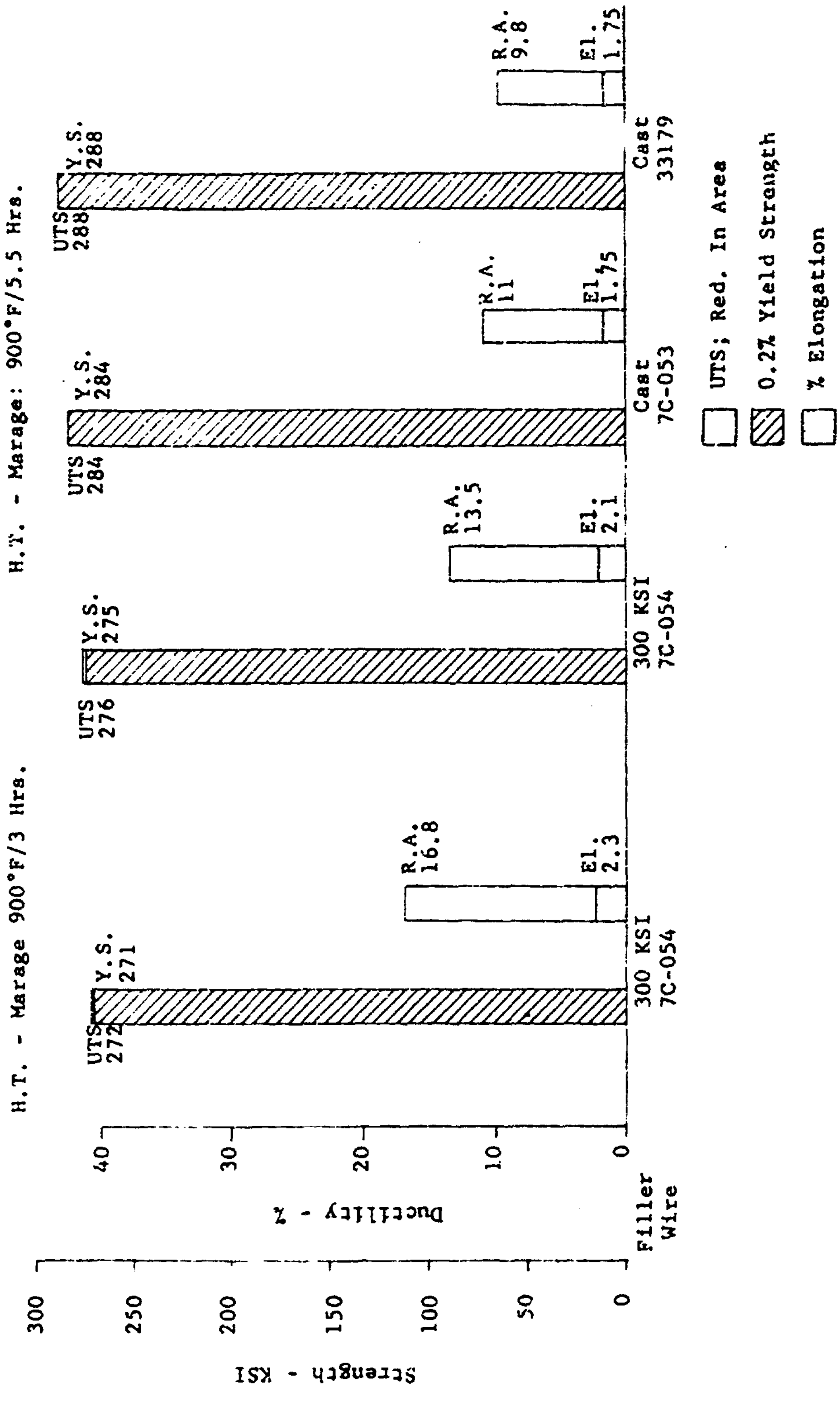


Figure 117

COMPARISON OF FILLER WIRES
TRANSVERSE WELD FRACTURE TOUGHNESS PROPERTIES
18% NICKEL ALLOY (300 KSI)-0.140" SHEET

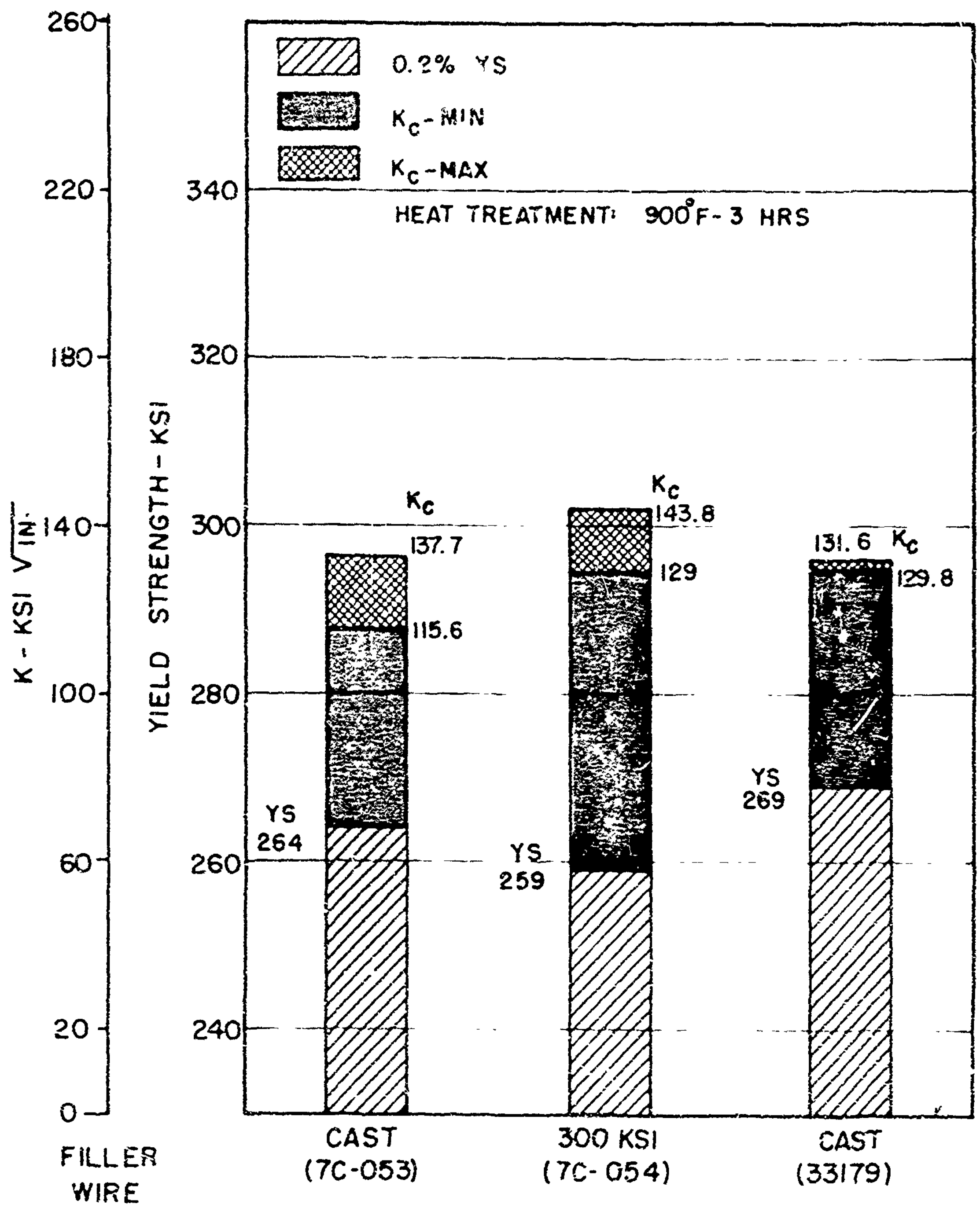


Figure 118

COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE AND FRACTURE TOUGHNESS PROPERTIES
18% NICKEL ALLOY (300 KSI)-0.140" SHEET

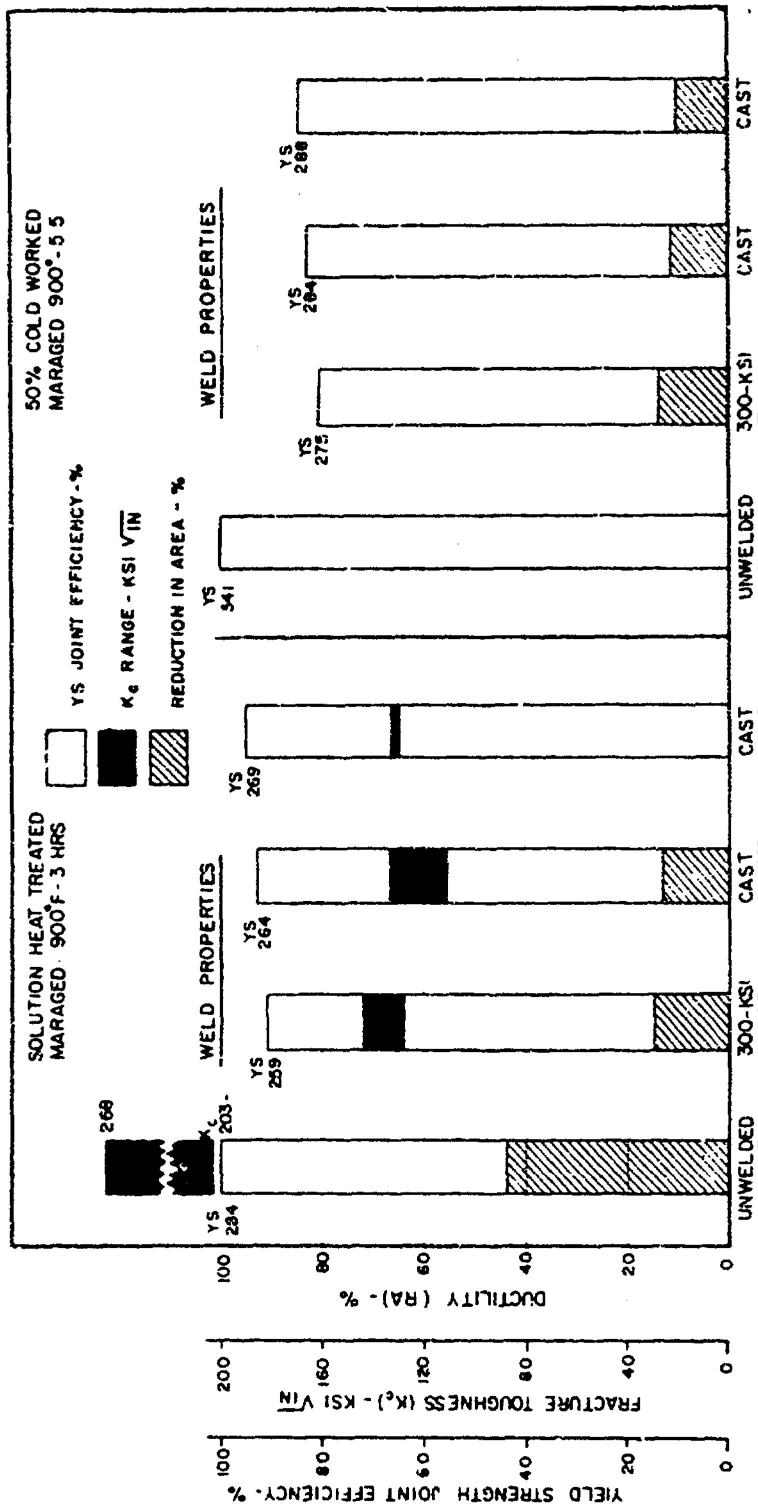


Figure 119

Table 42

EFFECT OF SOLUTIONING TIME AND TEMPERATURE ON THE HARDNESS OF 18% NI ALLOY (300 KSI)*

Solution** Temp. °F	Solution Time Hrs.	As Quenched Hardness Rc	Maraged*** Hardness Rc
1400	¼	39.0	53.4
	½	37.5	54.4
	1	37.0	55.0
	2	36.0	53.3
	4	35.5	54.3
1500	¼	34.1	53.8
	½	32.8	54.9
	1	33.0	55.0
	2	33.0	54.8
	4	33.0	54.2
1600	¼	32.5	54.4
	½	32.5	53.7
	1	32.0	54.0
	2	31.9	54.0
	4	32.0	53.8
1700	¼	31.0	53.2
	½	30.1	53.1
	1	30.0	53.0
	2	30.0	54.0
	4	30.0	52.3
1800	¼	30.0	53.3
	½	29.0	53.2
	1	27.5	53.0
	2	29.0	53.0
	4	28.6	53.0
1900	¼	30.0	53.4
	½	30.0	53.1
	1	29.0	53.0
	2	29.0	52.0
	4	28.3	52.2

Table 42 (Cont.)

EFFECT OF SOLUTIONING TIME AND TEMPERATURE
ON THE HARDNESS OF 18% NI ALLOY (300 KSI)* (cont'd)

Solution** Temp. °F	Solution Time Hrs.	As Quenched Hardness Rc	Maraged*** Hardness Rc
2000	¼	34.8	52.8
	½	33.8	52.0
	1	35.0	53.0
	2	34.0	52.0
	4	34.0	52.7
2100	¼	28.0	
	½	28.5	
	1	29.0	
	2	28.4	
	4	28.0	

* Allegheny Heat No. 23831

** All specimens maraged @ 900°F for 3 hrs.

*** Average of 6 readings

Table 43

EFFECT OF MARAGING PARAMETERS ON THE HARDNESS OF SOLUTION ANNEALED** 18% NI ALLOY (300 KSI)*

Marage Temp.	Marage Time	Hardness*** Rc
700	¼	39.5
	½	41.0
	2	47.6
	5	45.0
	9	45.4
800	¼	48.0
	½	48.1
	2	50.8
	5	52.1
	9	52.9
900	¼	50.6
	½	52.4
	2	54.0
	5	54.5
	9	54.7
1000	¼	51.2
	½	52.0
	2	52.2
	5	52.5
	9	53.3

* Allegheny Heat No. 23831

** Solution Anneal: 1500°F/1 hr.

*** Average of 6 readings

Table 44

Effect of Solution Time and Temperature

on the

Longitudinal Tensile Properties of 18% Nickel Alloy *(300 KSI)

Solution Temp ** ^{o}F	Solution Time Hrs.	Ult. Tensile Strength KSI	0.2% Yield Strength KSI	% Elong.	% Red. in Area
1400	1	307	295	2.8	21
1400	1	318	313	3.6	35
1500	½	297	290	6.0	53
1500	½	300	290	4.5	33
1500	1	291	281	4.7	42
1500	1	291	282	5.0	46
1500	1-½	294	287	6.0	53
1500	1-½	295	281	6.0	41
1500	2	298	286	5.0	38
1500	2	290	279	5.0	51
1600	1	284	269	5.0	49
1600	1	287	275	5.0	44
1700	1	279	267	5.0	45
1700	1	289	275	6.0	44

** All specimens solution annealed (argon atmosphere) under the above conditions, air quenched and, then, maraged at 900°F for 3 hours.

* Allegheny Ludlum Heat No. 23831.

Table 45

Effect of Solution Time and Temperature

on the

Transverse Tensile Properties of 18% Nickel Alloy *(300 KSI)

Solution Temp ** °F	Solution Time	Ult. Tensile Strength KSI	0.2% Yield Strength KSI	% Elong.	% Red. in Area
1400	1 Hr.	322	315	1.4	32
1400	1 Hr.	323	320	2.8	32
1400	1 Hr.	321	312	2.9	32
1400	1 Hr.	328	315	3.0	34
1500	1 Hr.	304	289	4.0	40
1500	1 Hr.	297	282	2.2	41
1500	30 Min.	311	304	4.0	41
1500	30 Min.	312	307	5.0	41
1500	1 Hr.	302	284	4.0	42
1500	1 Hr.	310	298	3.0	41
1500	1.5 Hrs.	308	293	4.9	41
1500	1.5 Hrs.	319	305	5.0	29
1500	2 Hrs.	303	289	4.0	38
1500	2 Hrs.	293	283	5.0	31
1600	1 Hr.	309	296	4.0	40
1600	1 Hr.	297	286	1.9	41
1600	1 Hr.	297	292	5.0	33
1600	1 Hr.	295	286	3.6	42
1700	1 Hr.	293	279	4.0	37
1700	1 Hr.	293	276	5.0	36
1700	1 Hr.	299	281	5.0	40
1700	1 Hr.	296	280	4.0	40

** All specimens solution annealed (argon atmosphere) under the above conditions, air quenched and, then, maraged at 900°F for 3 hours.

* Allegheny Ludlum Heat No. 23831.

Table 46

EFFECT OF SOLUTION TREATMENT ON FRACTURE TOUGHNESS OF 18% Ni ALLOY* (300 KSI)

Orientation of Specimen Axis to Rolling Direction	Solution** Temp. °F	Solution Time Hrs.	0.2% Yield Str. KSI	Net Fracture Stress(1) KSI	Notch Strength KSI (2)	β (3)	Critical Crack Index (4)	Kc (5) $KSI\sqrt{In}$	Gc (6) + $In\text{-}lbs/in^2$
Parallel	1400	1	304	170	76	0.65	0.02	83	270
			304	120	71	0.65	0.02	83	270
Normal	1400	1	315	79	66	0.29	0.01	58	132
			315	92	64	0.36	0.01	65	165
Parallel	1500	½	290	233	202	3.65	0.13	187	1380
			290	228	194	3.50	0.13	18[illegible]	1320
Normal	1500	½	305	176	144	1.56	0.06	131	685
			305	199	148	1.93	0.07	143	809
Parallel	1500	1	281	249	191	4.58	0.17	203	1630
			281	254	189	4.75	0.17	207	1690
			282	297	242	7.79	0.24	208	2830
			287	253	216	4.60	0.17	208	1700
Normal	1500	1	285	208	140	2.67	0.10	158	980
			285	216	132	3.05	0.11	167	1100

* Allegheny Ludlum Heat No. 23831
** All specimens maraged at 900°F for 3 hrs.
\+ Centrally notched, fatigue cracked specimens

TABLE 47

EFFECT OF MARAGING TREATMENT ON THE LONGITUDINAL TENSILE PROPERTIES OF SOLN. ANNEALED 18% NICKEL ALLOY* (300 KSI)

Marage Temp °F	Marage Time Hrs.	Ult. Ten. Str. KSI	0.2% Yield Str. KSI	% Elong.	% R.A.
850	1	257	243	7	47
"	1	256	246	7	49
"	3	275	269	5	47
"	3	279	265	6	49
"	10	307	293	5	49
"	10	302	292	4	60
900	1	273	263	5	50
"	1	279	267	7	48
"	3	287	281	6	51
"	3	298	286	6	47
"	10	302	297	4	42
"	10	308	296	4	48
950	1	291	282	5	44
"	1	290	287	4.5	50
"	3	296	284	5	44
"	3	300	288	4	48
"	10	299	287	6	54
"	10	296	281	5	48

* All specimens solution annealed at 1500°F for 1 hour, air quenched, and, then, maraged under the above conditions

TABLE 48

EFFECT OF MARAGING TREATMENT ON THE TRANSVERSE TENSILE PROPERTIES OF SOLN. ANNEALED 18% NICKEL ALLOY* (300 KSI)

Marage Temp °F	Marage Time Hrs.	Ult. Ten. Str. KSI	0.2% Yield Str. KSI	% Elong.	% R.A.
900	1	279	271	6	52
"	1	281	267	5.5	50
"	3	306	294	4	47
"	3	305	296	4	50
850	10	312	299	4.5	39
"	10	311	293	5	43
"	1	256	246	6	43
"	1	262	247	6	42
"	3	281	269	5.5	35
"	3	280	271	5	43
900	10	312	297	4	34
"	10	310	298	4	34
950	1	295	288	4	47
"	1	302	286	4.5	37
"	3	309	295	5	47
"	3	304	290	4	35
"	10	307	295	5	40

* All Specimens solution annealed at 1500°F for 1 hour, air quenched, and, then, maraged under the above conditions

Table 49

EFFECT OF MARAGING TREATMENT ON FRACTURE TOUGHNESS OF SOLUTION TREATED 18% NICKEL ALLOY* (300 KSI)

Orientation of Specimen Axis to Rolling Direction	Maraging** Temp. °F	Maraging Time Hrs.	0.2% Yield Str. KSI	Net Fracture Stress(1) KSI	Notch Strength(2) KSI	β (3)	Critical Crack Index(4) in	K_c (5) KSI in	Gc (6) † in-lb/in^2
Parallel	900	1	265	252	234	5.82	0.21	215	1830
"	"		265	261	246	6.38	0.23	225	2000
Normal	"		268	234	200	4.37	0.16	192	1450
"	"		268	217	187	3.56	0.14	174	1210
Parallel	"	3	283	232	201	3.80	0.14	186	1300
"	"		283	225	206	3.63	0.13	181	1290
Normal	"		295	208	154	2.48	0.09	159	1000
"	"		295	198	163	2.30	0.09	154	936
Parallel	"	10	295	208	182	2.72	0.10	163	1050
"	"		295	201	174	2.58	0.09	157	980
Normal	"		295	133	116	1.02	0.04	99	387
"	"		295	145	139	1.19	0.04	109	472

* Allegheny Ludlum Heat No. 23831

** All specimens solution treated @ 1500°F for 1 hour

† Centrally notched, fatigue cracked specimens

TABLE 50

LONGITUDINAL TENSILE PROPERTIES OF COLD WORKED 18% NICKEL ALLOY (300 KSI)

% Reduction	Marage Temp °F	Marage Time Hours	Ult. Tens. Str. KSI	0.2% Yield Str. KSI	% Elong.	% R.A.
20	850	1	275	268	5.4	32
"	"	1	286	285	5	42
"	900	1	309	307	4.8	47
"	"	1	316	316	4.3	49
"	850	3	284	284	4.5	49
"	"	3	290	286	4.4	44
"	900	3	313	311	4.6	49
"	"	3	323	320	4.0	49
"	850	10	331	330	4.2	48
"	"	10	330	326	4.3	47
"	900	10	327	326	3.7	50
"	"	10	325	324	4.8	49
30	850	1	294	283	4.5	47
"	"	1	299	299	4	20
"	900	1	317	315	4.7	52
"	"	1	324	324	3.7	49
"	850	3	309	308	4.5	48
"	"	3	306	306	4.0	49
"	900	3	330	329	4.5	49
"	"	3	326	325	1.7	46
"	850	10	333	332	4.0	49
"	"	10	333	331	4.4	42
"	900	10	332	329	4.3	49
"	"	10	332	327	4.2	51
40	850	1	302	294	3.7	37
"	"	1	315	311	4	46
"	900	1	335	334	2.1	48
"	"	1	328	326	4.5	51
"	850	3	316	316	4.5	49
"	"	3	317	315	4.0	45
"	900	3	317	317	3.9	47
"	"	3	338	333	4.5	49
"	850	10	338	333	4.2	51
"	"	10	342	342	3.9	46
"	900	10	342	340	4.0	47
"	"	10	338	333	3.7	43

TABLE 50 (continued)

% Reduction	Marage Temp °F	Marage Time Hours	Ult. Tens. Str. KSI	0.2% Yield Str. KSI	% Elong.	% R.A.
50	850	1	330	328	3	23
"	"	1	328	327	3	44
"	900	1		FAILED AT PINHOLE		
"	"	1		FAILED AT PINHOLE		
"	850	3		FAILED AT PINHOLE		
"	"	3	327	327	3.7	46
"	900	3		FAILED AT PINHOLE		
"	"	3		FAILED AT PINHOLE		
"	850	10	338	333	4.2	51
"	"	10		FAILED AT PINHOLE		
"	900	10	347	346	4.4	46
"	"	10		FAILED AT PINHOLE		
70	850	1	317	308	3.9	30
"	"	1	310	308	4	36
"	900	1	328	325	4.0	41
"	"	1	324	323	4.1	45
"	850	3	316	313	4.0	40
"	"	3	313	313	3.4	25
"	900	3	344	342	4.5	42
"	"	3	334	332	4.0	46
"	850	10	336	334	3.1	34
"	"	10	337	336	4.2	33
"	900	10	337	333	4.0	44
"	"	10		FAILED AT PINHOLE		

TABLE 51

TRANSVERSE TENSILE PROPERTIES OF COLD WORKED 18% NICKEL ALLOY (300 KSI)

% Reduction	Marage Temp °F	Marage Time Hours	Ult. Tens. Str. KSI	0.2% Yield Str. KSI	% Elong.	% R.A.
20	850	1	301	298	2.1	31
"	"	1	313	310	1.8	40
"	900	1	323	317	4.3	38
"	"	1	342	342	2.5	41
"	850	3	317	313	3.8	36
"	"	3	313	305	3.0	41
"	900	3	332	329	2.8	40
"	"	3	351	349	4.2	37
"	850	10	343	340	4.0	36
"	"	10	348	346	3.8	36
"	900	10	354	351	2.6	15
"	"	10	340	337	3.5	40
40	850	1	312	309	3.2	12
"	"	1	325	322	2.6	24
"	900	1	FAILED AT PINHOLE			
"	"	1	346	344	2.8	29
"	850	3	327	325	3.0	29
"	"	3	334	330	3.5	29
"	900	3	275	FAILED AT PINHOLE		
"	"	3	341	FAILED AT PINHOLE		
"	850	10	248	FAILED AT PINHOLE		
"	"	10	304	FAILED AT PINHOLE		
"	900	10	328	" " "		
"	"	10	315	" " "		
50	850	1	316	FAILED AT PINHOLE		
"	"	1		" " "		
"	900	1		" " "		
"	"	1		" " "		
"	850	3		" " "		
"	"	3		" " "		
"	900	3		" " "		
"	"	3		" " "		
"	850	10		" " "		
"	"	10		" " "		

TABLE 51 (Continued)

% Reduction	Marage Temp °F	Marage Time Hours	Ult. Tens. Str. KSI	0.2% Yield Str. KSI	% Elong.	% R.A.
50	900	10		FAILED	AT	PINHOLE
"	"	10		"	"	"
70	850	1	308	301	2.1	2
"	"	1	320	319	3.	25
"	900	1	353	350	2.2	5
"	"	1		FAILED	IN	PINHOLE
"	850	3	326	323	2.0	16
"	"	3	328	324	2.4	14
"	900	3		FAILED	IN	PINHOLE
"	"	3		"	"	"
"	850	10		"	"	"
"	"	10		"	"	"
"	900	10		"	"	"
"	"	10		"	"	"

Table 52

EFFECT OF COLD WORK & MARAGING PARAMETERS ON FRACTURE TOUGHNESS OF 18% NICKEL ALLOY* (300 KSI)

% Reduction	Orientation of Specimen Axis to Rolling Direction	Maraging Temp °F	Maraging Time Hrs	0.2% Yield Str. KSI	Net Fracture Stress(1) KSI	Notch Strength(2) KSI	β (3)	Critical Crack Index(4) in	Kc(5) $KSI\sqrt{in}$	Gc(6) $in\text{-}lb/in^2$
20	Parallel	900	3	311	284	214	4.26	0.17	226	2020
"	"	"	"	320	235	193	2.65	0.10	182	1310
30	Parallel	850	10	332	206	157	1.61	0.07	152	910
"	"	"		331	205	171	1.71	0.07	157	980
		900	3	329	234	187	2.42	0.09	179	1260
		"	"	325	233	193	2.42	0.10	179	1270
			5.5	328	226	179	2.30	0.09	174	1196
				328	221	182	2.18	0.08	169	1107
	Normal			334	153	113	0.89	0.04	111	480
				334	165	101	0.92	0.04	114	514
40	Parallel	850	10	333	167	128	1.06	0.04	122	585
				342	166	135	1.05	0.04	122	585
	Normal			349	109	94	0.42	0.02	80	252
				349	129	92	0.56	0.02	91	330
	Parallel	900	3	325	169	142	1.29	0.05	126	632
				325	165	140	1.18	0.05	124	615
			10	340	168	127	1.04	0.04	122	595
				333	161	124	0.97	0.04	117	540
	Normal		3	341	111	96	0.46	0.02	81	260
				341	97	94	0.34	0.01	70	199
			10	347	98	88	0.32	0.01	72	205
				347	99	86	0.32	0.01	72	207
50	Parallel	850	10	333	135	110	0.75	0.03	99	382
				333	146	117	0.89	0.03	107	433
	Normal			353	87	78	0.25	0.01	63	156
				353	83	68	0.23	0.01	60	140
	Parallel	900	3	341	138	114	0.76	0.03	102	405
				341	138	113	0.76	0.03	101	402
			10	346	142	110	0.76	0.03	102	410
				346	150	105	0.79	0.03	106	445
	Normal		3	356	100	79	0.35	0.01	73	208
				356	111	83	0.42	0.02	80	235
			10	351	88	80	0.28	0.01	64	163
				351	86	80	0.25	0.01	62	156
70	Parallel	900	3	337	157	129	1.04	0.04	118	550
				337	169	134	1.26	0.05	127	635
	Normal			352	106	83	0.41	0.02	77	235
				352	97	78	0.34	0.01	70	193

TABLE 53

LONGITUDINAL TENSILE PROPERTIES OF WARM WORKED 18% NICKEL ALLOY (300 KSI)

Warm Work Temp. °F	Marage Temp. °F	Marage Time Hours	Ult. Tens. Str. KSI	0.2% Yield Str. KSI	% Elong	% R.A.
1200	850	1	194	192	12.5	46
"	"	1	191	184	12	50
"	900	1	199	190	8	43
"	"	1	194	185	8	41
"	850	3	207	200	8	49
"	"	3	198	186	9	40
"	900	3	202	192	10	44
"	"	3	204	185	9	63
"	850	10	186	180	7	40
"	"	10	205	201	9	47
"	900	10	193	177	[illegible]	40
"	"	10	198	188	7	41
1400	850	1	273	266	6	34
"	"	1	274	266	5	36
"	900	1	292	283	5	51
"	"	1	293	284	5	51
"	850	3	298	288	5	42
"	"	3	290	284	5.5	35
"	900	3	307	297	5	58
"	"	3	301	296	5	49
"	850	10	294	289	5	45
"	"	10	308	305	6	45
"	900	10	304	301	4	43
"	"	10	304	303	4	46
1600	850	1	240	225	7	36
"	"	1	335	226	6	41
"	900	1	254	243	6	40
"	"	1	248	233	6	45
"	850	3	267	251	5	40
"	"	3	256	242	6	31
"	900	3	281	266	6	52
"	"	3	276	267	5	54
"	850	10	263	259	5	36
"	"	10	280	273	5	33
"	900	10	292	281	4	45
"	"	10	297	288	3	39

TABLE 54

TRANSVERSE TENSILE PROPERTIES OF WARM WORKED 18% NICKEL ALLOY (300 KSI)

Warm Work Temp. °F	Marage Temp. °F	Marage Time Hours	Ult. Tens. Str. KSI	0.2% Yield Str. KSI	% Elong	% R.A.
1200	850	1	209	199	16	58
"	"	1	193	172	10	51
"	900	1	192	176	16	30
"	"	1	188	169	12	41
"	850	3	233	226	16	46
"	"	3	202	178	14	55
"	900	3	186	172	14	47
"	"	3	196	180	17	59
"	850	10	176	167	13	58
"	"	10	177	169	15	57
"	900	10	189	169	10	47
"	"	10	191	182	12	56
1400	850	1	275	265	4	44
"	"	1	279	269	5	42
"	900	1	294	284	4	45
"	"	1	291	280	5	39
"	850	3	280	270	4	40
"	"	3	306	298	3.5	33
"	900	3	308	304	4	39
"	"	3	306	303	5	45
"	850	10	293	290	4	33
"	"	10	317	314	4	27
"	900	10	305	299	3	33
"	"	10	308	305	3	34
1600	850	1	238	224	6	38
"	"	1	242	220	6.5	27
"	900	1	266	252	6	41
"	"	1	265	243	7	53
"	850	3	248	232	4	43
"	"	3	273	259	-	34
"	900	3	292	277	5	39
"	"	3	294	283	5	41
"	850	10	268	262	6	35
"	"	10	294	283	6	43
"	900	10	297	283	5	41
"	"	10	295	291	4	45

Table 55

EFFECT OF MARAGING TREATMENT ON FRACTURE TOUGHNESS
OF WARM WORKED 18% NICKEL ALLOY * (300 KSI)

Warm Working Temp. °F	Orientation of Specimen Axis to Rolling Direction	Maraging Temp. °F	Maraging Time hrs.	0.2% Yield Str. KSI	Net Fracture Stress (1) KSI	Notch Str. (2) KSI	β (3)	Critical Crack Index (4) in	K_c (5) $\frac{KSI}{\sqrt{in}}$	G_c † (6) in.lb/in^2
1200	Parallel	900	10	183**		189				
	"	"	"	183**		199				
1400	Parallel	900	3	297	210	159	2.34	0.09	158	987
	"	"	"	297	219	170	2.87	0.10	169	1130
	"	"	10	302	253	122	1.53	0.05	134	712
1400	Normal	900	3	304	139	138	1.74	0.66	138	761
	"	"	10	302	146	115	1.05	0.40	108	457
	"	"	"	302	152	107	1.10	0.42	110	470
1600	Parallel	900	10	285	190	140	2.25	0.08	141	790
	"	"	"	285	204	126	2.26	0.08	142	800

* Allegheny Heat No. 23831

† Centrally notched, fatigue cracked specimens

** Specimens tore through pin holes

Table 56

Shearspinning Procedures For 18% Nickel

Pass No.	Roller Setting Front	Rear	Feed Rate	RPM	Roller Nose Radius	Front Roller Lead
1	.310	.260	7"/min.	280	0.750"	0.375"
2	.250	.180	4"/min.	280	0.750"	0.375"
*3	.115	.080	12"/min.	280	0.750"	0.375"
4	.064	.046	6"/mim.	280	0.750"	0.375"

* Solution annealed before third pass at 1500° F-1 hours.

TABLE 57

WELD SETTINGS

<u>18% Ni SUBSCALE BOTTLES</u>

Process:	Gas Tungsten-Arc (Single Pass)
Wire:	18% Ni-300 KSI (7C-054)
Wire Dia:	.062"
Electrode:	2% Thoriated W, 5/32" Dia.
Electrode Location:	.250" off center table rotation; clockwise weld direction; counterclockwise off center
Current:	80-90 Amps
Voltage:	15.5 volts
Travel:	9 ipm
Wire Feed:	21 ipm
Gas Flow-	
Nozzle:	30 cfh He
Back Up:	4 cfh He
Trial:	14 cfh He
Back Up:	Copper

Table 58

REPAIR WELDING PROCEDURE

DEFECT ROUTED AND DYE PENETRANT INSPECTED

Preheat:	300-400° F
Post Heat:	None
Gas Flow:	
Nozzle:	15 CFH Argon
Back Up:	10 CFH Helium
Electrode:	2% Thoriated W
Electrode Dia:	3/32"
Current:	60 amps
Back Up:	Copper
Filler Wire:	18% Ni-300 KSI (7G054)

TABLE 59

18% NICKEL MARAGING STEEL

[illegible] BURST TESTS

VESSEL SPECIFICATIONS	BURST PRESSURE (PSIG)	GAGES	PROPORTIONAL LIMIT BIAXIAL	UNIAXIAL	BIAXIAL GAIN	0.2% YIELD STRENGTH BIAXIAL	UNIAXIAL	BIAXIAL GAIN %	ULTIMATE PSI BIAXIAL	UNIAXIAL	BIAXIAL GAIN %	MAX	REMARKS	PB/t
Forged and Machined un-welded	7700	5 & 6	256,00	219,400	16.7	327,000	280,000	16.5	323,000	311,000	14.2*		No Gage read at burst	
		7 & 8	252,000	219,400	14.9	327,000	280,600	16.5	335,000	291,000	15.1*	2.1743	Gages C did not read at burst	345,000
Forged and machined un-welded	7760	1 & 2	252,000	219,470	14.9	326,000	280,470	16.2	332,000	291,000	16.1*		No gage read at burst	
		7 & 8	254,000	219,400	15.8	330,000	280,600	17.4	337,000	291,000	17.5*	1.9300	Gage B did not read	348,000
Forged and Machined girth welded	6920	1 & 2	234,000	219,400	13.8	328,000	280,700	16.9	327,800	291,000	10.9	1.1970		310,300
Forged and Machined girth welded tested	7470	1 & 2	258,000	219,400	17.5	327,500	280,400	16.7	338,000	291,000	16.2*	-	Reading at burst press.	335,000
Shear spun un-welded	7900	3 & 4							344,000	279,600	18.5	1.0335	Failure before reaching 0.2% yield	349,000
		5 & 6							339,600	289,600	16.6	1.0143		
		7 & 8							337,800	290,400	16.2	1.0143		
Shear spun girth welded	6750	3 & 4							287,500**	270,600	-	0.9110	Failure before reaching 0.2% yield	302,700

* Actual value could not be obtained from test

** Vessel failed prematurely

TABLE 60

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 18% (300 KSI) MARAGING NICKEL STEEL

Smooth Bar Tensile Data

Location	% Reduction	Heat Treatment	U.T.S. (KSI)	0.2% Y.S. (KSI)	% Elong.	% R.A.
Billet						
Vertical-Center	0	1500°F/1 hr.	288.4	283.0	12.0	39.5
Vertical-Edge	0	900°F/3 hrs.	288.6	280.6	14.0	54.5
Horizontal-Center	0		285.4	275.0	10.0	41.1
Horizontal-Edge	0		297.4	288.1	5.0	14.5
First Upset						
Vertical-Center	33.8		286.2	274.5	9.0	41.3
Vertical-Edge	33.8		286.5	274.3	9.0	39.6
Horizontal-Center	33.8		283.5	274.5	3.0	14.7
Horizontal-Edge	33.8		288.6	278.3	5.0	17.1
Second Upset						
Vertical-Center	50		280.2	270.9	9.0	43.1
Vertical-Edge	50		290.5	279.6	10.0	44.2
Horizontal-Center	50		275.2	265.0	6.0	16.2
Horizontal-Edge	50		289.6	289.6	9.0	34.8
Third Upset						
Vertical-Center	66.2		273.8	271.8	9.8	56.9
Vertical-Edge	66.2		286.0	282.1	10.5	72.0
Horizontal-Center	66.2		278.8	267.9	4.0	7.1
Horizontal-Edge	66.2		285.4	275.0	10.0	41.1
Fourth Upset						
Vertical-Center	75		276.2	274.3	5.6	8.0
Vertical-Edge	75		283.8	282.1	8.4	43.0
Horizontal-Center	75		285.8	275.4	6.0	16.8
Horizontal-Edge	75		289.8	278.9	8.0	40.4
Fifth Upset						
Vertical-Center	84		274.4		1.8	5.2
Radial	84		285.0	277.0	11.0	50.7
Circumference	84		289.4	280.6	10.0	41.3

TABLE 60 (Cont'd.)

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 18% (300 KSI) MARAGING NICKEL STEEL

Notch Bar Tensile Data

Location	% Reduction	Heat Treatment	U.T.S. (KSI)	K_{1c} (KSI In)	G_{1c}
First Upset					
Vertical-Center	33.8	1500°F/1 hr.	347.9	72.0	205
Vertical-Edge	33.8	900°F/3 hrs.	347.4	77.6	238
Horizontal-Center	33.8		226.5	46.9	87
Horizontal-Edge	33.8		292.9	60.6	146
Second Upset					
Vertical-Center	50		337.1	69.7	193
Vertical-Edge	50		354.7	73.5	214
Horizontal-Center	50		351.6	72.7	209
Horizontal-Edge	50		333.1	69.0	189

Table 61

Critical Fracture Toughness Parameters of 18% Nickel Alloy (300 KSI)*

Condition	Heat Treat	N.T.S. K.S.I.	K_{1C} KSI $\sqrt{in}$	G_{1C}** PSI in-lb/in^2	$\frac{N.T.S.}{U.T.S.}$ ratio
Annealed	Sol'n: 1500°F/1 Hr.	321	62.6	155.0	1.10
	Marage: 900°F/3 Hrs.	320	60.5	144.6	1.10
		333	61.5	149.3	1.14
30% Cold Work	Marage: 900°F/5.5Hr.	407	84.4	281.3	1.25
		413	85.6	289.6	1.27
		415	86.0	292.5	1.28
40% Cold Work		396	82.1	263.4	1.18
		406	84.2	280.0	1.20
50% Cold Work		422	87.5	302.5	1.25

* Allegheny Heat No. 23831.

** Critical fracture toughness calculated from circumferentially-notched tensile bars (K_t = 10).

Table 62

WELD HEAT AFFECTED ZONE HARDNESS DATA - SPH (1)
18% NICKEL ALLOY (300 KSI) - HORIZONTAL TRAVERSE (2)

Base Material	Condition(3)	Distance From Weld Interface - in. .015	.030	.045	.060	.075	.090	.105	.120	.135	.150	.165	.180	.195	.210	.225	.250	.275	.300	.325	.350
Solution Heat Trea	As-Welded	326	332	350	334	332	341	330	354	339	435	309	431	441	389	364	350	354	343	347	350
	Aged	590	609	588	593	583	609	609	609	609	614	604	614	598	588	593	598	603	603	598	598
30% Cold Worked	As-Welded	361	350	330	339	347	376	376	402	429	464	333	-	497	454	438	416	411	-	-	-
	Aged	603	61.	609	614	630	641	619	647	635	630	641	-	603	641	658	670	658	670	676	-

(1) Diamond Pyramid Hardness, 10KG load, 136° apex angle

(2) Traverse taken along sheet centerline

(3) Aged: 900°F/3 hrs., air cool

Table 63

TRANSVERSE WELD TENSILE PROPERTIES
18% NICKEL ALLOY (300 KSI) - SOLUTION HEAT TREATED 0.140" SHEET (1) (2)

Filler Wire		Marage						Average Properties				Joint Eff.-%	
Type	Heat No	Temp °F	Time Hrs.	UTS KSI	0.2% YS KSI	Elong %	R.A. %	UTS KSI	0.2% YS KSI	Elong. %	R.A. %	T.S.	Y.S.
300 KSI	7C-054	900	3	265	263	2.5	14.3	260	259	2.5	15.1	88	91
				260	259	3.0	16.5						
				256	255	2.0	14.7						
Cast	7C-053	900	3	265	262	2.5	9.0	267	264	2.5	13.2	91	93
				268	267	2.5	13.0						
				268	265	3.0	17.8						
				265	262	2.0	12.9						
Cast	33179	900	3	281	277	2.3	17	271	269	2.2	14.5	93	95
				266	261	2.1	11						
				261	261	2.5	18.2						
				276	277	2.0	11.8						

(1) Sheet rolling direction parallel to orientation of specimen axis

(2) All specimens failed in weld

Table 64

TRANSVERSE WELD TENSILE PROPERTIES
18% NICKEL ALLOY (300 KSI) - 50% COLD WORKED 0.140" SHEET (1) (2)

Filler Wire		Marage						Average Properties				Joint Eff.-%	
Type	Heat No	Temp °F	Time Hrs.	UTS KSI	0.2% YS KSI	Elong %	R.A. %	UTS KSI	0.2% YS KSI	Elong %	R.A. %	T.S.	Y.S.
300 KSI	7C-054	900	3	271 272	271 272	2.5 2.0	18.6 14.9	272	271	2.3	16.3	81	81
	7C-054	900	5.5	283 269	280 269	1.9 2.3	7 20	276	275	2.1	13.5	81	81
Cast	7C-053	900	5.5	283 285	283 284	1.5 2.0	8.4 13.6	284	284	1.75	11.0	83	83
Cast	33179	900	5.5	286 289	286 289	2.0 1.5	11.5 8.2	288	288	1.75	9.8	84	85

(1) Sheet rolling direction parallel to orientation of specimen axis

(2) All specimens failed in weld

Table 65

TRANSVERSE WELD FRACTURE TOUGHNESS PROPERTIES

18% NICKEL ALLOY (300 KSI)- 0.140" SHEET

FILLER WIRE TYPE	FILLER WIRE HEAT NO.	MARAGE TEMP. (°F)	MARAGE TIME (hrs.)	0.2% YIELD STR. (KSI)	NET FRACTURE STRESS (KSI)	NOTCH STRENGTH (KSI)	β	CRITICAL CRACK INDEX (in)	K_c KSI $\sqrt{in}$	G_c in-lb/in^2
Cast	7C-053	900	3	264	154	121.8	1.67	.061	115.6	528.3
				264	186.7	137.6	2.17	.080	132.7	696.2
300 KSI	7C-054	900	3	259	199.5	129.9	2.38	.098	*143.8	917.3
				259	174.3	132.1	1.85	.079	129.0	657.3
Cast	33179	900	3	269	175.4	130.9	1.714	.076	131.6	685
				269	195.3	121.4	1.65	.074	129.8	666.1

Table 66

COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE AND FRACTURE TOUGHNESS PROPERTIES
10 % NICKEL ALLOY (300 KSI)

Base Material		Filler Wire		Maraging		Average Weld Properties							Unwelded Sheet Properties					
										Joint Efficiency-%							K_c - KSI $\sqrt{in.}$	
Condition	Thickness in.	Type	Heat No.	Temp. °F	Time Hours	UTS KSI	0.2% Y.S. KSI	Elong. %	R.A. %	TS	Y.S.	K_{Ic} KSI $\sqrt{in}$	UTS KSI	0.2% Y.S. KSI	Elong. %	R.A. %	Longitudinal	Transverse
Solution Heat Treated (1)	0.140	300 KSI	7C-034	900	3	260	257	1.5	15.1	68	81	129-144	293	284	4.5	44	203-268	150-167
		Cast	7C-033	900	3	267	264	1.5	13.2	71	93	126-155						
		Cast (2)	33179	900	3	271	269	2.2	14.3	93	92	130-132						
30% Cold Worked	0.140	300 KSI	7C-034	900	5.5	276	[illegible]	2.1	13.5	81	81	-	343(3)	341(3)	-	-	101-106(3)	62-80(3)
		Cast	7C-033	900	5.5	284	264	1.75	21.0	82	83	-						
		Cast (2)	33179	900	5.5	288	288	1.75	9.8	84	83	-						
Solution Heat Treated (1)	0.070	300 KSI	7C-034	900	3	261	262	1.6	20.8	89	92	-						
		Cast	7C-033	900	3	257	258	1.5	16.2	88	91	-						

(1) Unwelded sheet solution heat treated 1500°F/1 hour

(2) High cobalt, copper-free type

(3) These values represent estimates based on best available data

1.0 PHYSICAL METALLURGY

1.1 Transformation and Hardening Mechanisms

The "martensite transformation" in iron-nickel alloys has been the subject of many investigations. The review in this report is limited to only a few aspects of the martensite transformation which are likely to enter into a discussion of the strengthening mechanisms of the iron-nickel alloys. This presentation does not include any discussion on the crystallography, thermodynamics and kinetics of the martensite transformation. The reader is referred to Wechsler, Lieberman, and Read (1), Bowles and Mackenzie (2, 3, 4), Bilby and Christian (5), Christian (6), Bullough and Bilby (7), Lieberman (8), Wechsler (9), and Bilby and Frank (10) for a discussion of the crystallography and Kaufman and Cohen (11, 12), Cohen (13, 14), Kurdjumov (15), and Holomon and Turnbull (16) for an analysis of the thermodynamic and kinetics of the martensitic transformation.

Martensite transformations have been discussed in considerable detail in a number of articles. The term has been used to designate a type of solid state, diffusionless, and shear-type phase transformation in metallic systems which is basically different from the familiar nucleation-and-growth type of transformation (17). The martensite transformation in iron-nickel systems in particular, has several interesting features which can be summarized as follows:

1. The transformation is attended by shear-like macroscopic displacements that results in surface tilts (5).

2. The transformation can proceed both athermally and isothermally (18).

3. The transformation usually proceeds by the nucleation of new plates rather than by the growth of pre-existing plates (17).

4. The isothermal nucleation is activated by thermal fluctuations superimposed on localized regions of very high strain (3).

5. No diffusion of alloying elements occurs during the transformation.

6. The composition of the martensite is identical with that of the austenite and any distribution of solute atoms (interstitial or substitutional) that exists in the parent phase is inherited by the martensitic product.

7. Section-size effects are small due to an insensitivity of the martensite reaction to cooling rate and the lack of higher

temperature - diffusion controlled austenite decomposition to carbide phases (18).

8. The martensite structure is body-centered cubic and does not exhibit any tetragonality (18).

9. Martensite is only moderately hard (R_C 25) and very tough (18).

10. M_s temperature is primarily determined by the chemical composition and it may be influenced to some extent by previous thermal and mechanical history and by grain size (17).

11. No tempering occurs when the martensite is reheated (18).

12. The hysteresis of the transformation (Figure 120) allows considerable reheating of the martensite for aging before reversion to austenite occurs (18).

The above features have been drawn from the indicated review papers in order to point out the unique characteristics of the iron-nickel system. As seen from the above summary, the nature of the martensite transformation is complex and the information accumulated to date suggests that the strengthening in iron-nickel alloys is a composite of several strengthening mechanisms. Some of the important features of the martensitic transformation will now be considered in more detail.

1.1.1 Solid State Equilibrium in the Binary Iron-Nickel System

The equilibrium phase transformations have been studied by several investigators, i.e., Hansen (19), Desch (20), Marsh (21), and Benedicks (22). The last two reviews are the most recent.

The exact placing of the alpha and gamma phase boundaries was difficult because of the (a) formation of a body-centered cubic metastable martensitic phase which varies with composition and heat treatment and (b) low diffusion rates at temperatures below 500°C (23-26). As a result of these experimental problems, a number of proposed diagrams (23, 24, 27-30) are considered unreliable since they do not represent the equilibrium state.

The boundaries established by Owen and Sully (25) and Owen and Liu (26), utilizing long time annealing and X-ray diffraction techniques, are considered the most reliable. The results of both investigations agree closely except for (a) the gamma phase boundary in the 500-700°C temperature range and (b) the alpha boundary below 400°C. The

boundaries presented in Figure 121 are those determined by Owen and Liu (26).

Boundaries calculated from free-energy relationships of the alpha and gamma phases (24, 31, 32) are in good agreement with those shown in Figure 121.

1.1.2 Martensitic Transformation in the Binary Iron-Nickel System

The martensitic transformation can occur both athermally and isothermally in iron-nickel alloys as in several other metallic systems. The athermal and isothermal characteristics which are of interest for the discussion of iron-nickel systems are reviewed in the following two sections.

1.1.2.1 Athermal Characteristics

The continuous cooling and heating curve is presented in Figure 122. This diagram, which was developed by Jones and Pumphrey (24) by dilatometric techniques is considered to be the most precise diagram available at present. Transformation temperatures found by other investigators (33-58) using thermal, dilatometric, thermoresistometric, thermomagnetic, and x-ray methods agree, in general, with those in Figure 122. There is appreciable controversy over the beginning and ending transformation temperatures as well as the width of the transformation temperature range. These discrepancies are attributed to experimental imperfections, i.e., lack of purity, homogeneity, etc.

It should be noted that the solid lines presented in Figure 122 are the temperatures corresponding to 10% and 90% transformation. The transformation temperature range is, therefore, slightly broader than shown.

The existence of the athermal characteristics of the martensitic transformation is evidenced by the temperature hysteresis effect indicated in Figure 122. This hysteresis for iron-nickel alloys (60) is shown in Figure 120 and is compared to that observed in gold-cadmium alloys (60) in Figure 123. In both systems, the athermal transformations are not suppressed by rapid cooling or heating (24, 61) and proceed while the temperature is changing. The athermal transformation, per se, is halted if cooling or heating is stopped. Transformation may continue, however, in instances where isothermal transformation occurs.

If the phenomenon of stabilization is operative, the athermal transformation may not start immediately after heating or cooling is resumed. Stabilization may also impede the isothermal reaction. The quantita-

tive and theoretical details of this phenomenon have been the subject of many investigations (59, 62-76). The latest theories suggest that carbon diffuses to the martensitic embryo-austenite interface. As a result, the interstitial atoms build up at the interface and render it immobile. Much controversy exists as to (a) the source of carbon, (b) the austenite or the martensite embryos and (c) what causes the concentration or activity gradient for the diffusion of carbon to the interface. The theories, however, do lend support to the hypotheses of Frank (77) and Cohen (78) which postulate a dislocation interface between the martensitic embryo and the surrounding phase.

The two hysteresis effects illustrated in Figure 121 represent two different reaction behaviors. According to Kaufman and Cohen (12), the iron-nickel martensite plates form successively with each platelet propagating rapidly until it encounters a structural barrier or its mechanism becomes jammed. No additional growth of the plate occurs on further cooling. Further transformation only occurs by nucleation elsewhere in the parent phase. As a result, the athermal transformation is dependent upon the nucleation rate and the final platelet size obtained and not on the rate of platelet growth. Microstructural investigations (79, 80) have shown this to be the case in both iron-nickel alloys and steels. Reactions of this type are characterized by a high degree of supercooling and, consequently, a relatively high degree of instability below the M_s.

Gold-cadmium martensite platelets, on the other hand, nucleate, appear suddenly, and propagate in length and thickness with decreasing temperature until collision or jamming occurs. This observation is in direct contrast to that which occurs in martensitic reactions of the iron-nickel type (12). Transformation in the gold-cadmium system takes place with relatively little supercooling and the driving force is insufficient to supply the requirements to form fully grown platelets. Since the available driving force is limited and a state of thermoelastic equilibrium is approached, the growth of a platelet may be stopped at a given temperature. A decrease in temperature increases the driving force and allows growth to proceed. Additional nucleation also takes place as the temperature decreases. From this, it may be stated that the rate of thermal transformation is dependent on the rate of propagation which is controlled by the rate of cooling.

Corresponding differences are also noted in the martensite-to-austenite transformations. Investigations by Edmondson and Ko (81) and Kaufman (82) on iron-nickel martensites have found that appreciable superheating is required to start reversion. The plates transform piecewise into smaller platelets rather than snap back out of existence. Gold-cadmium-type martensites revert with relatively little superheat-

ing. The plates shrink progressively and disappear in a manner approximating their formation (12). The reader is referred to other investigations (83-92) for discussions of reversion in other alloy systems.

Kaufman and Cohen (59) and Patel and Cohen (93) have shown the effect of plastic and elastic deformation on the transformation temperatures of iron-nickel alloys. The effect of plastic deformation on the M_s and A_s temperatures of 28-31 a/o nickel-iron alloys is presented in Figure 124. It can be noted that the hysteresis between the M_s and A_s is narrowed by plastic deformation. The M_s is raised, becoming the M_d, and the A_s is lowered, becoming the A_d. The midpoint between the M_d and A_d temperatures is the temperature at which martensite is in equilibrium with austenite or, in other words, the temperature at which the free energy of martensite is equal to the free energy of austenite. A similar effect on the M_s can be caused by elastic straining (93). The role of stress in shifting the transformation temperatures is a kinetic one. The nucleation process is stimulated by the stress so that the more stable phase, at a particular temperature, is formed (12).

1.1.2.2 Isothermal Characteristics

For many years, it was generally accepted that the progress of the martensitic transformation was not dependent on time but only on a decrease in temperature. It is interesting to note that Wever and Lange (94), as early as 1933, observed an isothermal mode in steels. This finding, however, was explained in conjunction with processes that involved secondary diffusion (80).

In recent years, isothermal transformations have been observed in some alloy systems. Enough information is available to rule out the necessity of athermal kinetics for a martensitic reaction. The isothermal mode in most systems, however, is either inoperative or obscured by the predominant athermal transformation.

In most instances where the isothermal reaction has been detected, it occurs below the M_s. Several cases of isothermal transformation above the M_s have been found (95-99) in various alloy systems including the iron-nickel system (73). Hence, it may be stated that athermal martensite is not required for isothermal transformation. Because martensite reactions are strain sensitive and autocatalytic in nature, the presence of athermal martensite may stimulate the nucleation of isothermal martensite when cooling is halted below the M_s (12).

The isothermal kinetics reveal a C-curve behavior, regardless of whether athermal martensite is present or not. In many instances, the

active temperature range extends well below room temperature with the maximum transformation rate found in the vicinity of 100-150°K (100).

In almost all cases, the formation of the martensite plates by the isothermal reaction is physically similar to that of the athermal transformation in iron-nickel alloys, i.e., nucleating of new plates rather than growth of existing ones. Such isothermal reactions are obviously controlled by the rate of nucleation (12). Only two cases have been reported in which the isothermal growth is analogous to the gold-cadmium type of progressive athermal growth, i.e., the isothermal bainite transformation in steels (101) and the uranium-chromium martensitic transformation (96, 102).

1.1.3 Strengthening of Martensite

Winchell and Cohen (17) have classified the possible sources of the strength of martensite. Their work has categorized the strengthening of martensite in two general groups:

a. Those that require preferential distribution of solute atoms before or during straining.

b. Those that apply when the solute atoms are randomly dispersed.

Specific mechanisms were considered and in the first group precipitation phenomena, dislocation - atmosphere interactions, interactions of solute atoms with faulted areas between partial dislocations, and clustering and short range order were postulated as possible strengthening mechanisms. In the second group, hardening by random solutes and by increase of elastic moduli were proposed.

Winchell and Cohen evaluated the relative contribution of each of the above mentioned mechanisms on a series of iron-nickel-carbon alloys whose nickel-to-carbon ratio was varied such that the M_s temperature was kept constant at about -40°C over a range of 0.01 to 1.0%C. The contribution of nickel to the strength of the alloys by substitutional solid solution strengthening was shown to be small and could therefore be neglected. Electrical resistivity and hardness measurements were first made at liquid-nitrogen temperatures immediately after quenching, before any decomposition of the martensite occurred. Measurements were then taken at successively higher temperatures up to 100°C, allowing 3 hrs for aging at each temperature. The electrical resistivity results are shown in Figure 125. The shape of the curves for electrical resistivity versus temperature clearly indicates the existence of aging phenomena. Measurements taken in a similar manner revealed the characteristic increase, then decrease, of hardness with aging temperature of a precipitation hardening phenomenon, as shown in Figure 126.

It is evident that the process is carbon dependent; hardening is practically absent at 0.0%C. The principal increase in hardness is between 0.0 and 0.2%C.

From tension and compression tests and the data presented above, Winchell and Cohen estimated the relative contributions of interstital solid solution hardening and precipitation hardening for the range of carbon contents investigated. The results are reproduced in Figure 127 (17). Although the lower curve is approximate, it is evident that intense solid solution hardening is confined to carbon contents below about 0.3%. Practically no additional strengthening of this kind is observed from 0.4 to 0.8%C. The relative contribution of precipitation hardening to the total strength of martensite may vary with alloy composition other than carbon content.

Since the temperature dependence of the flow stress of martensite is low at temperatures below which aging can occur, Winchell and Cohen concluded that elastic interaction of carbon atmospheres and dislocations is not the likely solid solution strengthening mechanism. Short-range order, clustering, and interaction of solute atoms with stacking faults require prior segregation and are also considered inprobable, since the hardening observed is present in as-formed martensite. Elastic modulus measurements showed that the modulus of carbon-containing iron-nickel alloys was less than that of the carbon-free alloys. Accordingly, the authors deduced that strengthening by carbon is not likely to be due to an increase in elastic constants. From this and other evidence, Winchell and Cohen concluded that the primary strengthening mechanisms of iron-nickel-carbon martensites are random solute strengthening in unaged specimens and precipitation hardening in aged martensites of higher carbon contents.

To summarize, the strengthening mechanism of iron-nickel alloys cannot be postulated as yet. The relative contribution of precipitation hardening to the total strength of martensite and the complex precipitates, which contribute to the hardening mechanism during maraging, have not been clearly defined. However, some evidence has been accumulated and this will be discussed in the next section when reviewing the precipitation hardened iron-nickel alloy development.

COMPOSITE RESISTANCE, TEMPERATURE CURVES FOR IRON-NICKEL ALLOYS SHOWING HYSTERESIS EFFECT

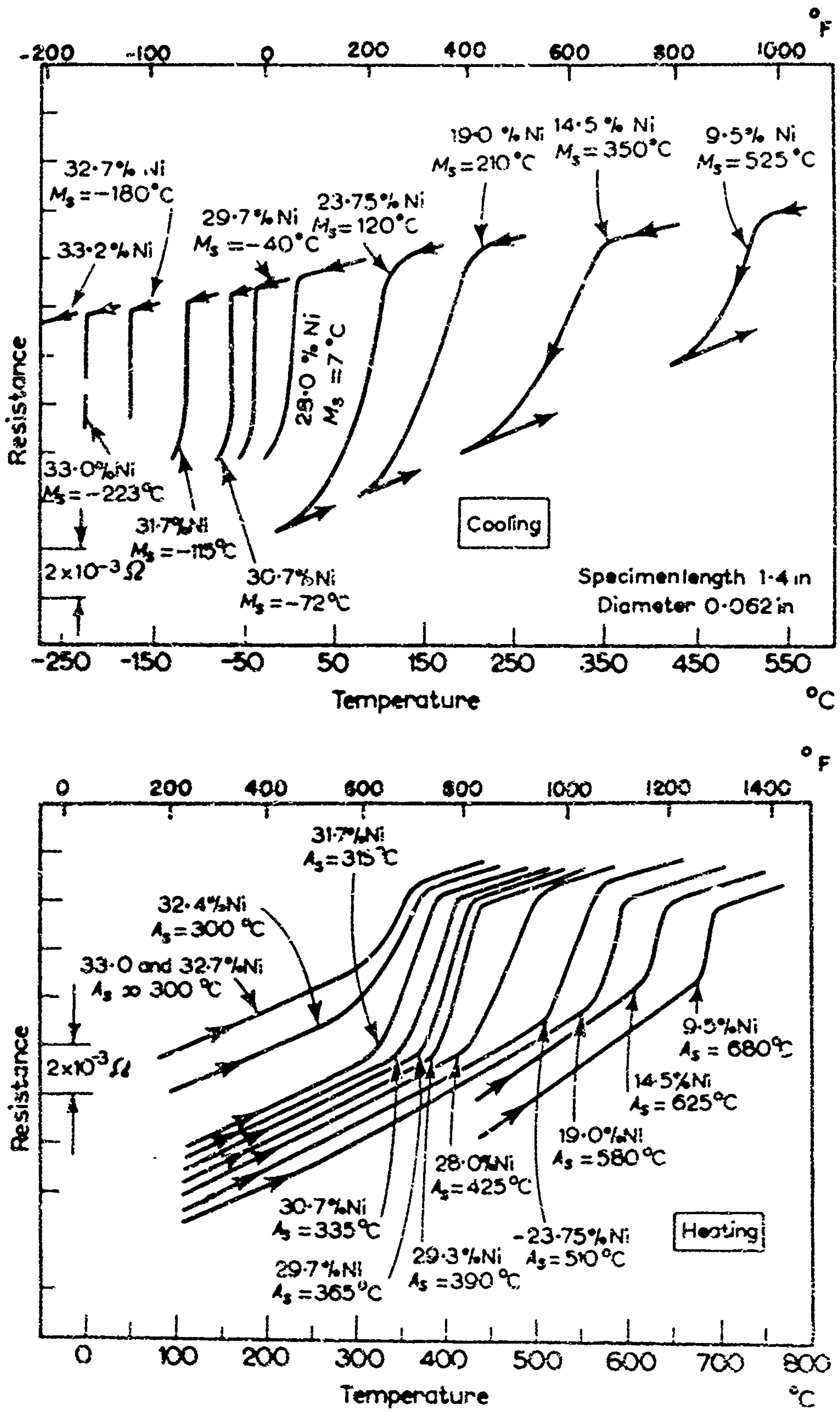


Figure 120

IRON - NICKEL EQUILIBRIUM DIAGRAM

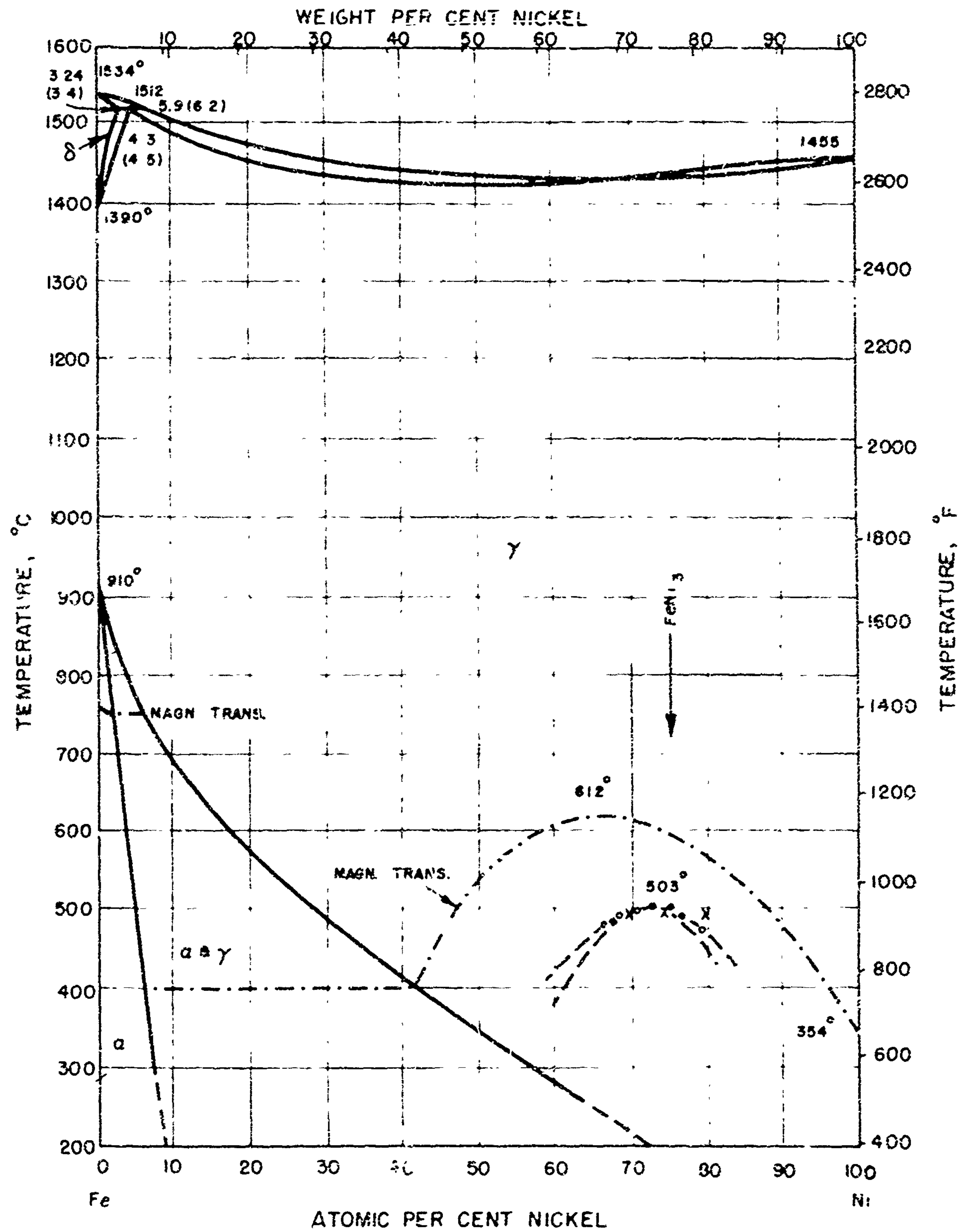


Figure 121

319

TRANSFORMATION DIAGRAM FOR CONTINUOUS HEATING AND COOLING OF IRON-NICKEL ALLOY

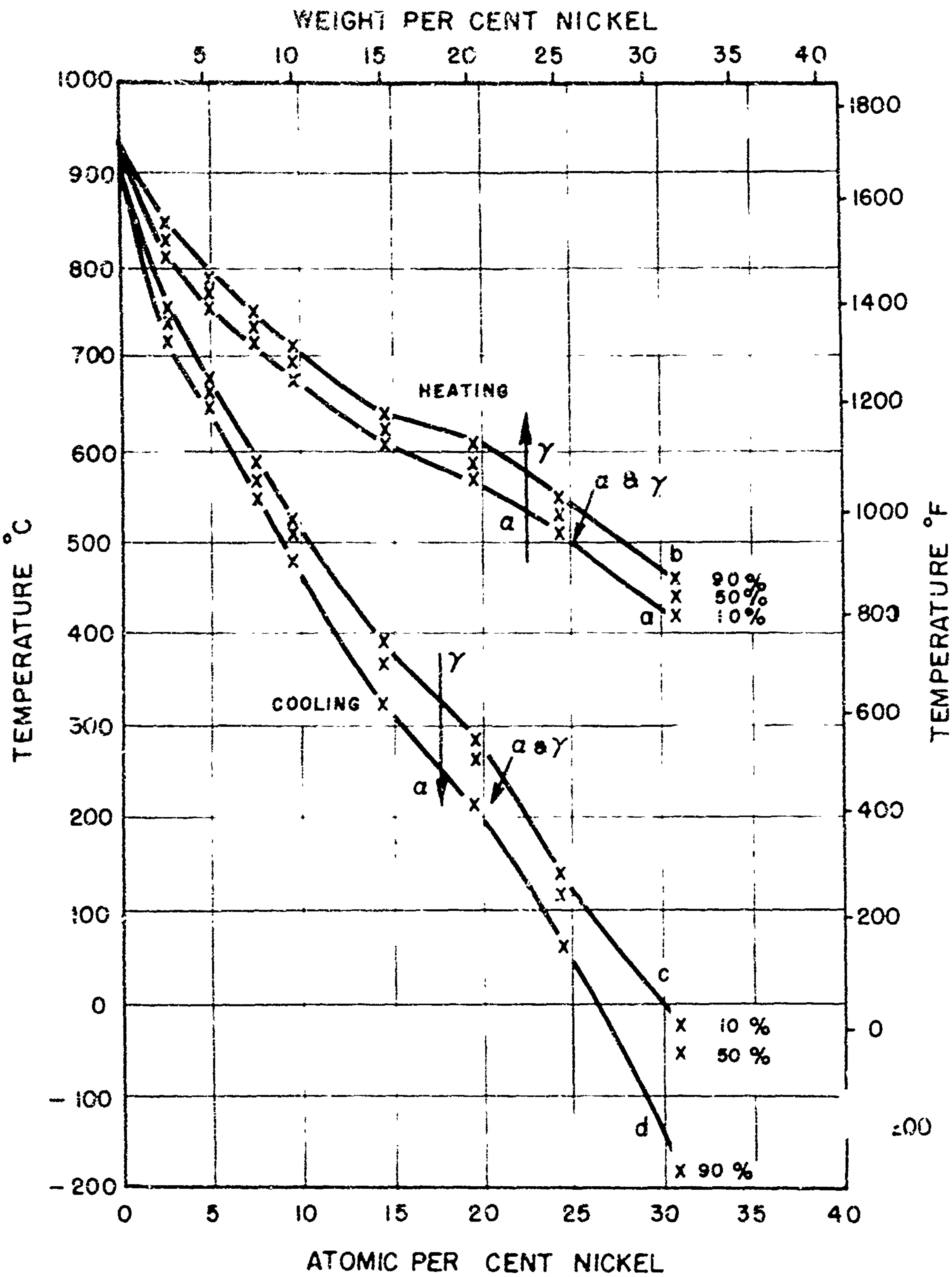
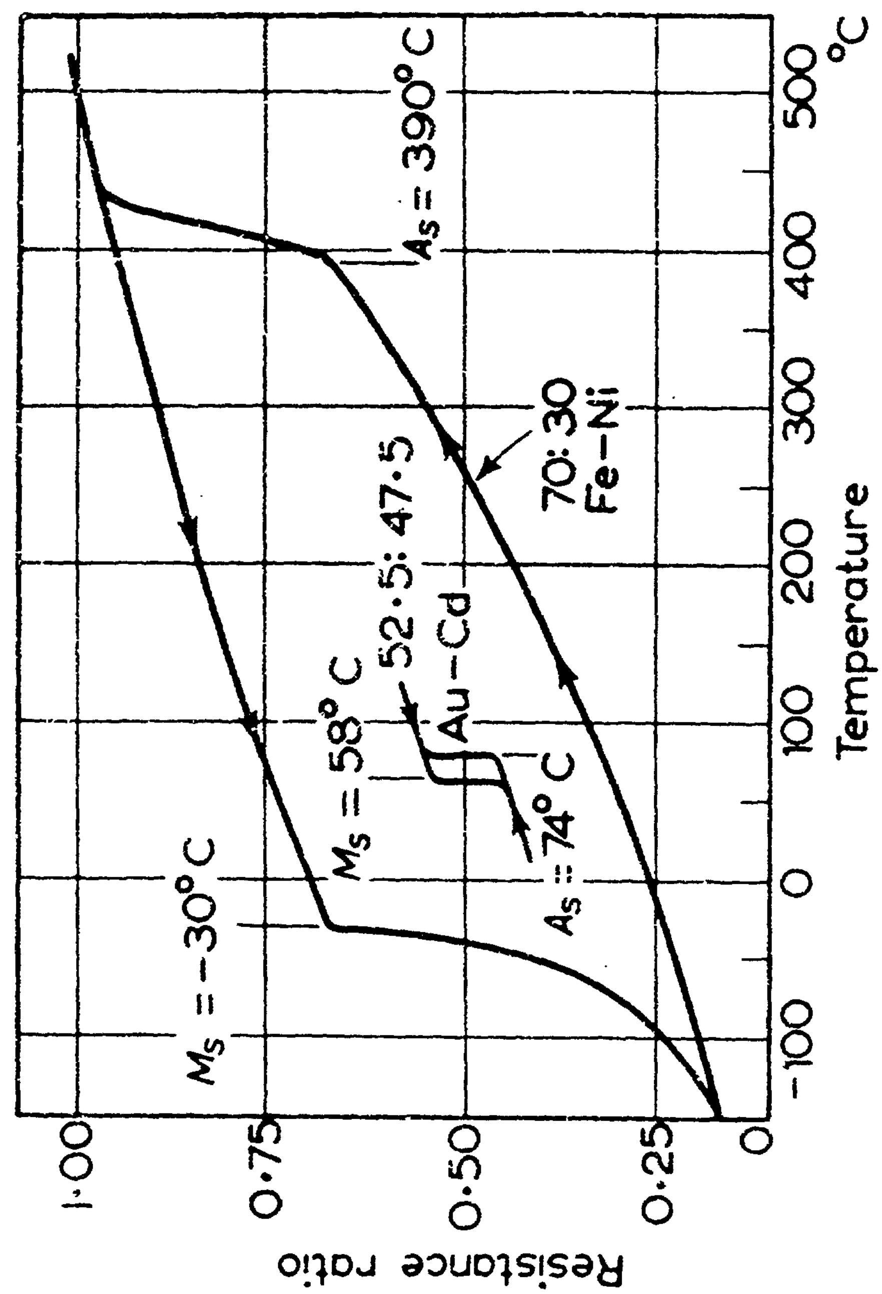


Figure 122

3439



ELECTRICAL RESISTANCE CHANGES DURING THE COOLING AND HEATING OF IRON-NICKEL AND A GOLD-CADMIUM ALLOY, ILLUSTRATING THE HYSTERESIS BETWEEN THE MARTENSITIC REACTION ON COOLING AND THE REVERSE TRANSFORMATION ON HEATING

Figure 123

EFFECT OF PLASTIC DEFORMATION ON TRANSFORMATION IN IRON-NICKEL ALLOYS

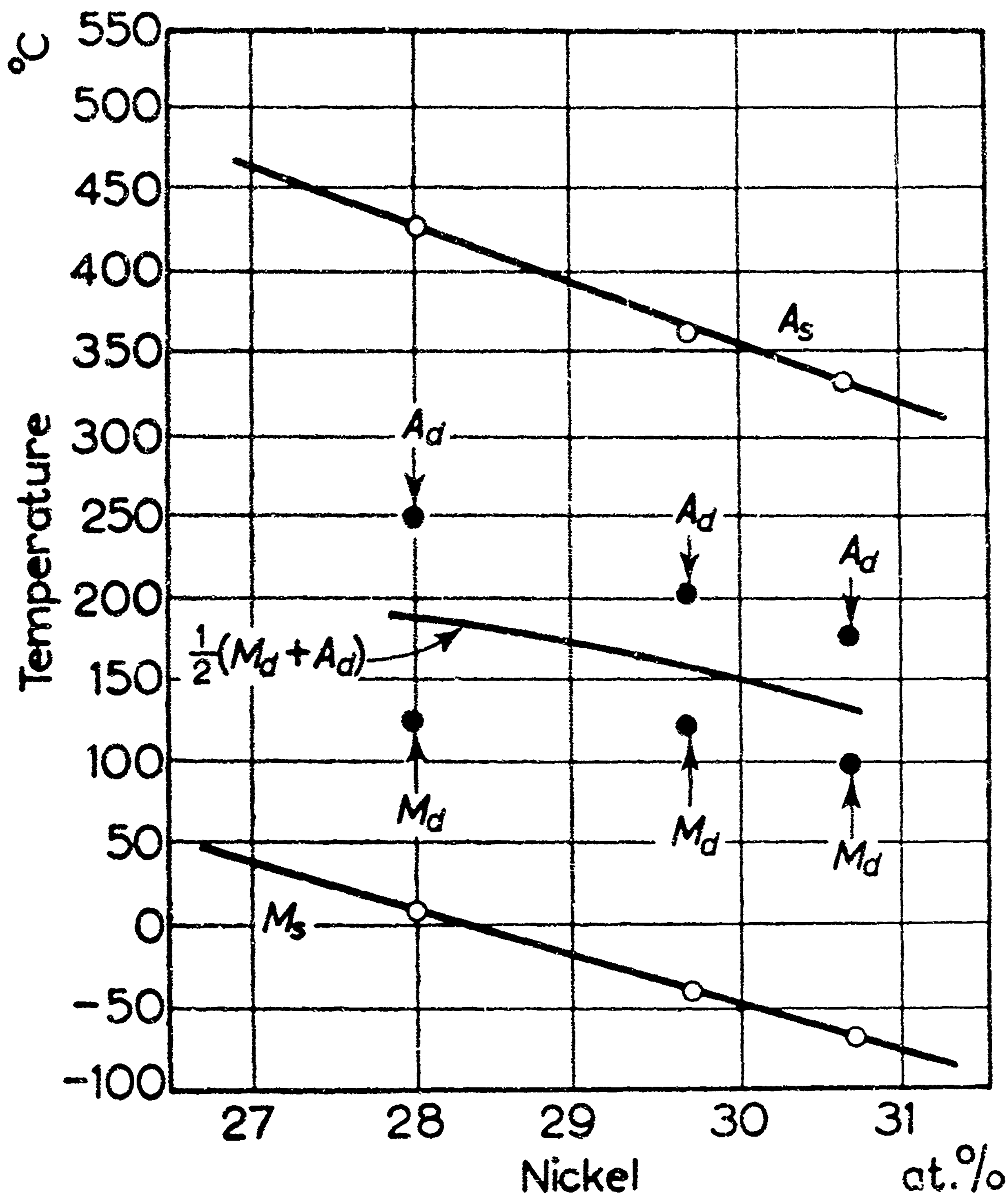


Figure 124

3440

CHANGE IN RESISTIVITY WITH AGING TEMPERATURE
FOR SEVERAL IRON-NICKEL-CARBON ALLOYS (109)

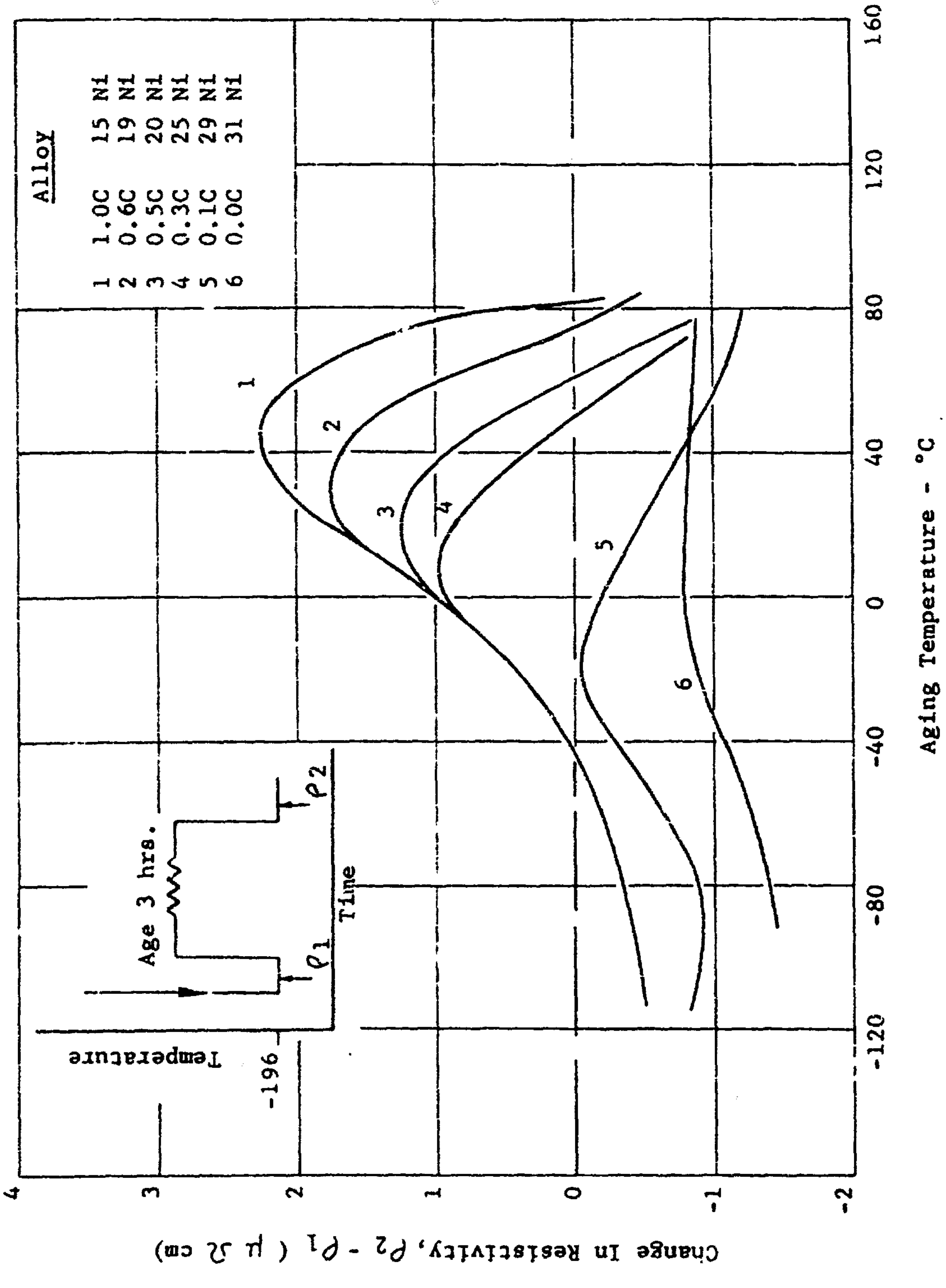


Figure 125

ROCKWELL C HARDNESS AT -196°C VS. AGING TEMPERATURE
FOR SEVERAL IRON-NICKEL-CARBON ALLOYS (109)

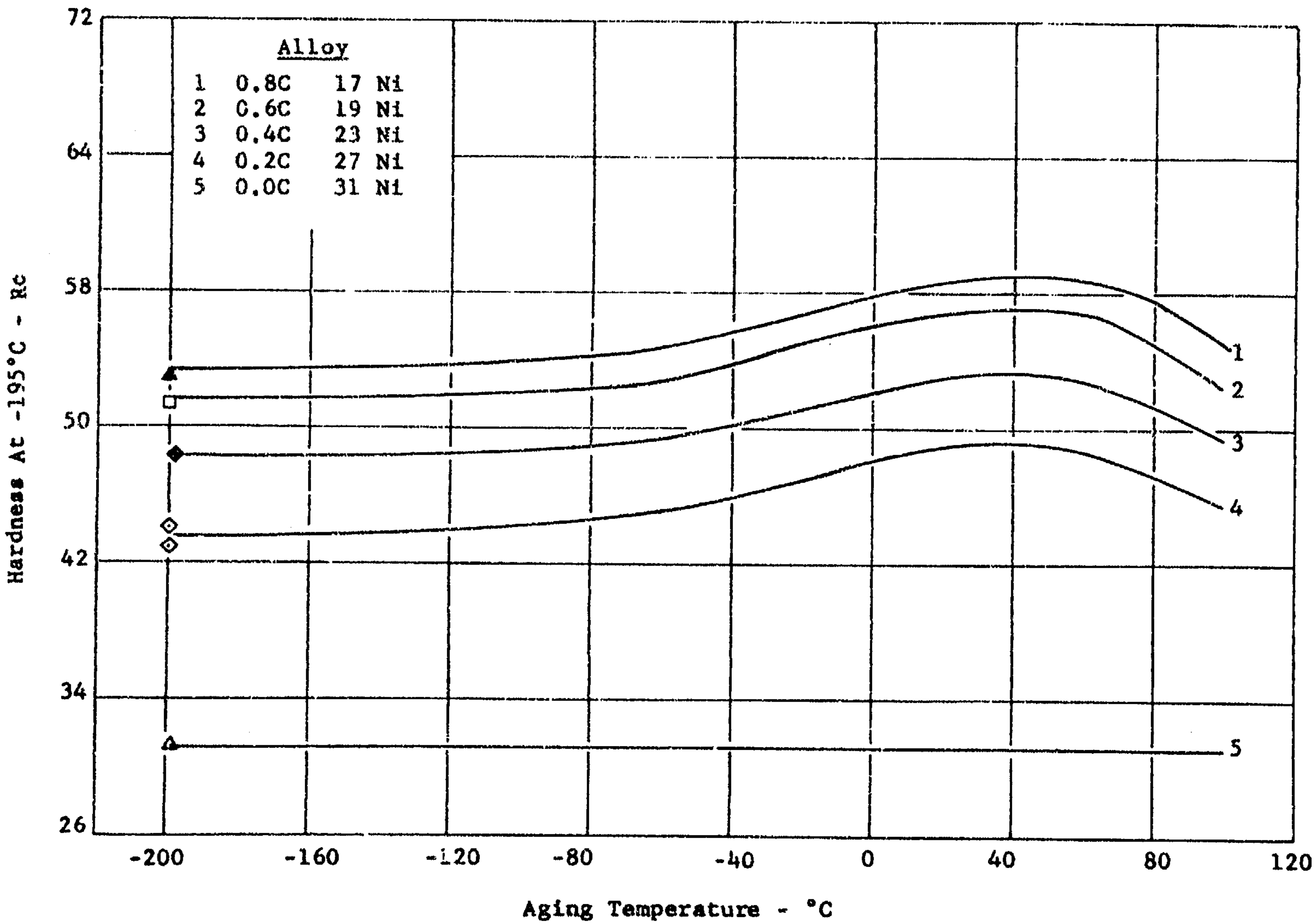


Figure 126

CONTRIBUTIONS OF SOLID SOLUTION STRENGTHENING AND
PRECIPITATION HARDENING TO THE YIELD STRENGTH OF MARTENSITE (109)

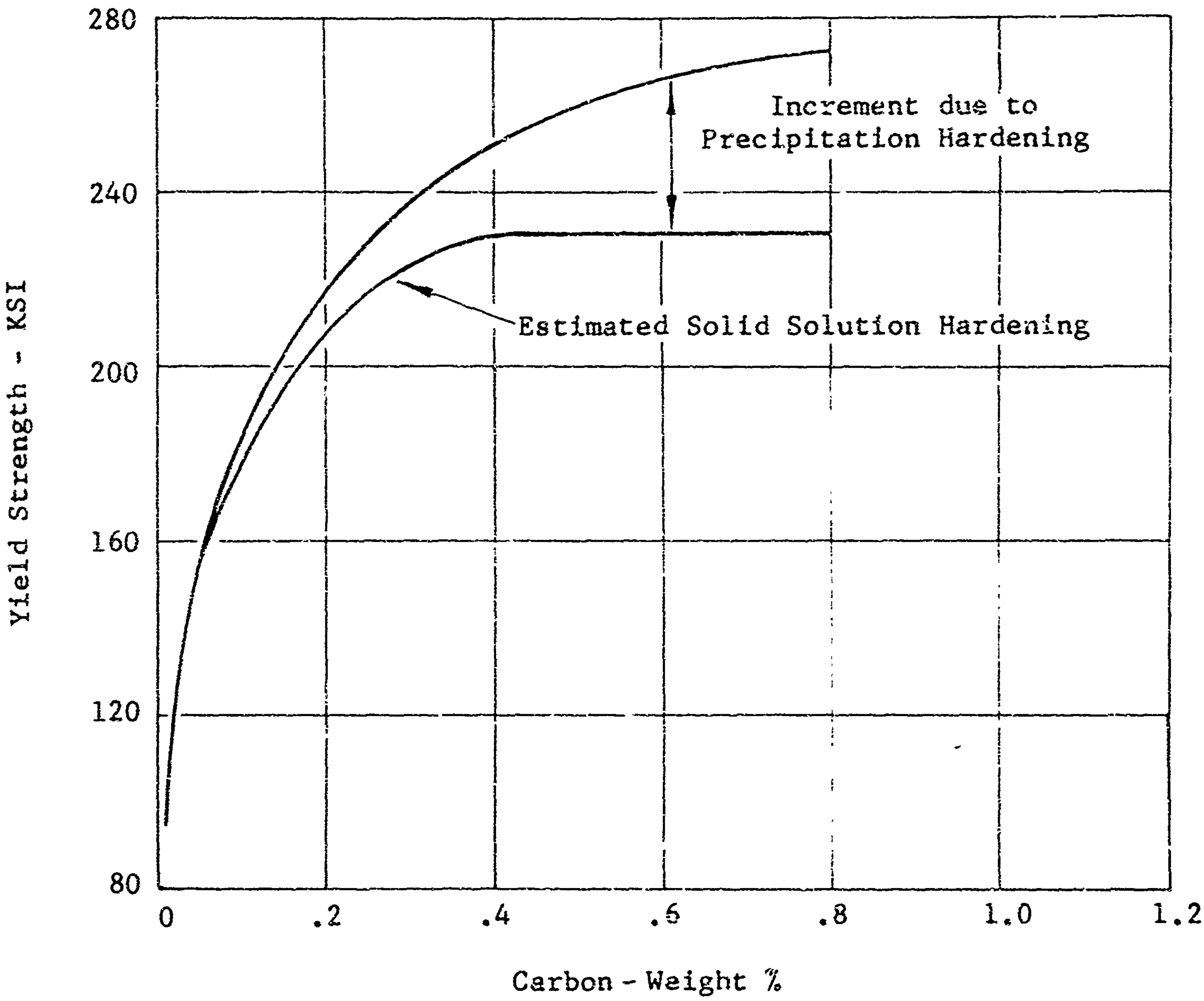


Figure 127

3909

1.2 Review of Precipitation Hardened Iron-Nickel Alloy Development

A unique property of the carbon-free, iron-nickel martensite is its extreme toughness. In contrast, the strength and hardness of these alloys are relatively low.

With the above two important facts in mind, the International Nickel Company, Inc. initiated a research program to strengthen the iron-nickel martensite to a level of engineering interest with a minimum loss of toughness. Emphasis was placed on studying the effect of various elements on the solid solution strengthening and precipitation hardening of the iron-nickel martensite. The development of the new class of promising alloys was a major accomplishment since Messrs. C. Bieber, R. Decker and associates had to overcome several complex obstacles. It is well known that the martensite transformation in even the simplest iron-base alloys is a composite of strengthening mechanisms and that the occurrence of any one of the solid state phenomena can either have a beneficial or an adverse effect on the mechanical properties and fracture characteristics of the alloy. It is pointed out that minor differences in the mechanical properties and fracture toughness responses can generally be explained by reviewing the chemical composition, grain size, thermal and mechanical history of the different heats. On this basis, the review in this section will be limited to a few important subjects.

1.2.1 Classification of Commercial Iron-Nickel Alloys

The research program initiated by INCO has produced, to date, four important alloys which can be classified into the following groups and sub-groups:

Group I: Alloys precipitation hardened with cobalt, molybdenum, and titanium. In this alloy class, two compositions have been developed.

a. 18% Nickel Alloy - 250 KSI nominal yield strength.

b. 18% Nickel Alloy - 300 KSI nominal yield strength.

The 300 KSI alloy is similar to the 250 KSI alloy, but uses higher cobalt and titanium levels for developing higher yield strength level.

Group II: Alloys precipitation hardened with aluminum and titanium. These alloy groups, in contrast to the Group I alloys, are free of any additions of cobalt and molybdenum. Two main compositions have been developed in this class.

a. 20% nickel alloy which is, essentially, martensite at room temperature in all conditions.

b. 25% nickel alloy which is largely austenitic at room temperature after solution annealing around 1500°F.

1.2.2 Influence of Composition on the M_s and Mechanical Properties of Iron-Nickel Alloys

The effect of various alloying elements on the M_s and mechanical properties of iron-nickel alloys are discussed below. It should be noted that the discussions and results have been summarized primarily from the alloy development conducted by INCO.

1.2.2.1 Effect of Hardening and Strengthening Elements in Group I (18% Nickel) Alloys

The hardening and strengthening in the Group I alloys is mainly due to the contribution of four principal elements, namely, cobalt, molybdenum, aluminum, and titanium. The strengthening mechanism in these alloys has not been clearly defined as yet. However, recent work indicates that a fine, complex, hexagonal Co, Mo, Ti precipitate contributes very significantly to the hardening reaction. Some of INCO's investigators believe that the precipitation of the complex phase during maraging may be accompanied by an order-disorder reaction. Extraction-replica techniques with electron-diffraction gave evidence of an ordered phase based on Fe_2CoNi. This evidence ties in with the remarkable rate of initial hardening which is not consistent with normal diffusion reactions (19).

Molybdenum, by itself, or in combination with cobalt, slightly increases the annealed hardness of an 18-20% iron-nickel alloy (Figures 128 and 129). This effect of molybdenum becomes more pronounced after maraging and is greater in the presence of cobalt. It should be noted that the aged hardness does not increase appreciably on increasing the molybdenum content above 8% or the percent cobalt times percent molybdenum value above 50. Cobalt, on the other hand, has a negligible effect on the annealed and aged hardness in the absence of molybdenum.

The yield strength of the alloy, as expected from the hardness relationships, increases with the cobalt and molybdenum contents. At the titanium contents indicated in Figures 130 and 131, there is a considerable range over which a yield strength of 250,000 psi can be obtained. The effect of cobalt and molybdenum on the notch properties of the material, however, imposes a definite restriction on the composition. While there is considerable flexibility in the cobalt content, the molybdenum should be less than 5.1% for good notch

properties (NTS/YS = 1.4 - 1.5). The notch strength decreases considerably for molybdenum contents above 5.1%. It is believed that this may be related to the solubility of molybdenum in austenite at the annealing temperature. These empirical data suggest that raising the yield strength from 250,000 psi level, with minimum loss of fracture toughness, can best be obtained by increases in cobalt content.

Additions of titanium proved to be a desirable supplemental hardener for cobalt and molybdenum - containing alloys. The annealed hardness, aged hardness and strength of the 18% Ni, 7% Co, 5% Mo alloy increases with increasing titanium content (Figures 132 and 133). Data in Figure 133 illustrates that as titanium was increased from 0.1 to 0.7%, the yield strength increased from 220,000 to 280,000 psi. This increase was about 10,000 psi for each .1% of titanium. The NTS/TS ratio decreased in air melts containing more than 0.4% Ti. This drop-off was very sharp for maraging at 900°F, dropping to a NTS/TS of 1 at 0.6 to 0.7% Ti. Maraging at 950°F gave higher notch tensile strength in the air melts at 0.5% Ti and above. A titanium content of 0.7% was found to be the upper limit to preserve the excellent air melting characteristics of these alloys. Above this level, dross and films developed. Titanium also neutralizes residual carbon and nitrogen by removing them from solution in the martensite.

The effects of aluminum additions were also studied. Aluminum, in amounts of approximately 0.5%, caused supplementary hardening but was detrimental to the notch properties. An addition of approximately 0.1%, however, is made to the alloy for deoxidation purposes. A slight strengthening effect is noted from this addition (103).

1.2.2.2 Effect of Residual Elements in Group I (18% Nickel) Alloys

Carbon, silicon, manganese, phosphorous, sulphur, and calcium are the residual elements in these alloys. Carbon is usually present in the range of 0.01 to .03%. There are some indications that increasing the carbon content from 0.01% to 0.04% causes an increase in yield strength of approximately 20,000 psi. Carbon up to .03% was not detrimental to notch-tensile strength at the 250,000 yield strength level. However, at a carbon level of .05%, there is an indication that the yield and notch strength is decreased (Figure 134).

From the collected data to date, it appears that maintaining a carbon content of .01 - .03% is desirable in these alloys. Carbon contents in excess of 0.03% have an adverse effect on the strength and toughness of the alloy. The effective titanium content is reduced by the formation of TiC thereby decreasing the strength of the material. Toughness is reduced by the solid solution strengthening effect of the carbon on the martensite.

The silicon and manganese contents of all the laboratory heats referred to in the above discussions were below 0.15 and 0.10%, respectively. When these elements are individually increased to 0.25% and above, the strength increases, but the ductility and notch strength are drastically affected. This is probably caused by the solution hardening and strengthening effects of these elements on the martensite.

High phosphorus and sulphur contents are believed to have the same effects on these materials as they do in carbon steels. Therefore, a 0.010% maximum has been placed on these elements.

Approximately 0.05% calcium is added to the heats to aid in deoxidation (104). The effect of calcium on toughness is unknown.

1.2.2.3 Effect of Boron and Zirconium on Group I (18% Nickel) Alloys

Additions of small amounts of boron (0.003%) and zirconium (0.01%) are made to enhance the toughness of the alloys. These elements are added since the earlier work by INCO on titanium hardened alloys proved that these elements retarded grain-boundary precipitation and, hence, enhanced toughness and stress corrosion resistance. The beneficial effect could be due to the grain boundary segregation of these elements which have atomic radii incompatible with intersitial or substitutional solution (19).

1.2.2.4 Effect of Hardening and Strengthening Elements in Group II (20 and 25% Nickel) Alloys

The hardening and strengthening in the Group II alloys is, essentially, due to only two elements, namely aluminum and titanium. Most of the strengthening in these groups of alloys is derived from the precipitation of titanium compounds namely, Ni_3 (Al Ti) and Fe_2Ti. Activation energies calculated from the hardness data indicate that the activation energy for the 20% nickel and 25% nickel alloys are between 30,000 and 39,000 cal/mole. The agreement in the activation energies indicate that the precipitates in both alloys in this group are identical or closely related in composition. However, the calculated values are considerably below the activation energy required for the diffusion of major elements in the nickel alloys. This discrepancy has not been completely explained but it is thought that the low activation energies may be caused by an abnormally high number of vacancies induced during warm working (103).

Most of the strengthening in this group of alloys is derived from titanium. The effect of titanium content on the mechanical and notch properties of 20% and 25% nickel alloys are presented in Figures 135, 136 and 137 (25% Ni) respectively. It can be noted from these

figures that in order to keep the notched tensile strength-to-ultimate tensile strength ratio above 1.0, the titanium content must not exceed 1.6%. As found in the Group I alloys, the yield strength decreases approximately 10,000 psi per 0.1% Ti. Hence, the heat to heat variation of titanium should be kept to a minimum.

Investigations have shown that the strength of titanium strengthened materials is increased with increasing aluminum content. Additions up to 0.35% aluminum may be utilized without adversely affecting the notch strength. Aluminum contents above 0.35% drastically reduce the toughness of the alloy to a point where the notched tensile strength to ultimate tensile strength ratio is substantially below unity (103).

The alloys used in obtaining the data in Figure 137 contained small amounts of aluminum and columbium. Without the addition of the aluminum, the yield strength curves would be displaced downward approximately 20,000 to 30,000 psi.

1.2.2.5 Effect of Residual Elements in Group II (20% & 25% Ni) Alloys

Carbon, silicon, manganese, phosphorous, sulphur and calcium are the residual elements in these alloys. The effects of carbon content on the properties of the material are not well established. Certain indications, however, have been noted. Carbon contents up to 0.03% seem to have a beneficial effect on the notch properties of the material. This is attributed to the reduction in precipitation of Fe_2Ti in the grain boundaries. The exact mechanism which is operative is unknown but it is speculated that the carbon atoms are preferentially located in grain boundaries. This would obstruct the short circuit diffusion paths in the grain boundaries and, hence, inhibit the precipitation of Fe_2Ti in these boundaries.

Carbon contents in excess of 0.03% have an adverse effect on the strength and toughness of the alloy. The effective titanium content is reduced by the formation of TiC thereby decreasing the strength of the material. Toughness is reduced by the solid solution strengthening effects of the carbon on the martensite.

Manganese and silicon contents in excess of 0.100 have a drastic effect on the notch toughness of 25% Nickel alloy. High manganese contents, 0.5% and greater, increase the tendency to retain austenite after solution annealing. To overcome this effect, a longer ausaging treatment or refrigeration treatment is required. If these added precautions are not taken, lower yield strengths result because of the weakening effect of the retained austenite. Silicon, in general, increases the strength and lowers the ductility of the alloy by solid solution strengthening.

The effects of increasing manganese and silicon contents above 0.15% in 20% Nickel alloy have not been well established. Hence, a maximum content of 0.10% of these elements are recommended until it is proved from statistical data of production heats that the higher additions of manganese and silicon have no detrimental effects on the notch properties of 20% nickel alloys.

High phosphorus and sulphur contents have approximately the same general effects in the iron-nickel alloys as those in carbon steels. Therefore, a 0.010% maximum is placed on these elements (104).

Approximately 0.05% Ca is added to the heat to aid in deoxidation. The effect of calcium on toughness is unknown.

1.2.2.6 Effect of Toughness Improving Elements on Group II (20% & 25% Ni) Alloys

Columbium additions increase the notch properties of the 25% nickel alloy. INCO found that the amount of the continuous Fe_2Ti phase, generally found in the grain boundaries of 25% nickel alloy, was reduced by increasing the columbium content from 0% to 0.25%. The cleanest grain boundaries were found at the 0.15 to 0.25% level. Additions of columbium causes the formation of a discontinuous globular-shaped phase in the grain boundaries which is believed to be an iron-columbium compound.

The effects of boron and zirconium on the notch toughness is illustrated in Figure 137. This phenomena is further demonstrated graphically in Figure 138. It can be seen that the optimum boron and zirconium contents are 0.003% and 0.02%, respectively (103).

No systematic variations in columbium, boron, and zirconium contents have been made to determine the effects of these elements on the 20% nickel alloys. Some indications, however, have been noted. Analysis of strength data obtained on production melted heats has indicated that columbium has a definite strengthening effect. A change in properties has been noted in heats with columbium contents which vary from the high to low side of the 0.30-0.50% specification. The optimum columbium content for this alloy is considered to be similar to that of the 25% nickel alloy.

Contrary to the results of the 25% nickel, no beneficial effects of boron and zirconium on notch toughness were noticed. Boron and zirconium additions should still be made until this phenomenon is further substantiated.

1.2.2.7 Effect of Nickel and Other Elements on the M_s Temperature

The balance of nickel and the various elements is very critical in order to ensure a martensitic structure in the 18% and 20% nickel alloys and an austenitic structure in the 25% Nickel alloy after air cooling from the solutioning temperature.

The approximate effect of the major constituents on the M_s temperature of the iron-nickel alloys can be summarized as follows:

Element	Effect on M_s	Extent of Effect
Nickel	Lowers	50°F/1% of element
Titanium	Lowers	100°F/1% of element
Aluminum	None	0°F/1% of element
Columbium	Lowers	90-100°F/1% of element
Molybdenum	Lowers	40°F/1% of element
Cobalt	Raises	10°F/1% of element

The transformation temperatures, M_s and M_f, of an 18.1% Ni, 7.0 Co, 5.0 Mo, 0.4 Ti were found to be 310°F and 210°F. The isothermal transformation temperatures of a 25% nickel alloy after annealing and ausaging stages are presented in Figure 139.

Special Metals, Inc., formerly the Metals Division of the Kelsey-Hayes Corporation, has performed an investigation on the effect of nickel and titanium on the M_s temperature of the 25% Nickel alloy. Transformation temperatures of the alloys were determined by dialatometric techniques. The effect of nickel content and heat treatment on the M_s and M_f temperatures of 1.51% titanium material is presented in Figures 140 and 141. The M_s temperature of annealed (1 hour at 1500°F) material and ausaged (4 hours at 1300°F) material decreases linearly with increasing nickel content by approximately 60 - 65°F per 1% of nickel.

Ausaging at 1300°F for 4 hours lowers the M_s temperature by approximately 170°F. The effect of nickel content on the M_f temperature is similar to that on the M_s with the exception that the relationship is not as linear. Ausaging, as above, lowers the M_f by approximately 170°F. The temperature difference between the M_s and M_f temperature is 145 - 155°F.

The effect of titanium content and heat treatment on the M_s and M_f temperatures of 25.70% nickel material is presented in Figures 142 and 143. The M_s temperature of annealed material decreases approximately 100°F for an addition of 1% of titanium. The addition of 1% of titanium increases the M_s temperature of ausaged material approxi-

mately 140°F. The effect of titanium content on the M_f temperature of annealed material is less pronounced while that on the M_f temperature of ausaged stock is more pronounced.

1.2.3 Composition Specifications

From the brief discussion presented in the above sections, it is evident that the composition of the various iron-nickel alloys should be carefully controlled in order to ensure the desired properties and structure. The critical elements in the 18% and 20% nickel alloys should be balanced so as to raise the M_s above room temperature. Attention is drawn to the fact that:

a. 18% and 20% nickel alloys should transform completely to 100% martensite after air cooling from the annealing temperature. If the elements in these alloys are balanced, any small amounts of retained austenite would transform isothermally within a short period of time.

b. 25% nickel alloy should have an austenitic structure after air cooling from the annealing temperature in order to facilitate forming in some severe fabrication processes.

After considering all the facts and the approximate ranges that can be met by various melting practices, the recommended composition specifications for the two groups of alloys are as presented in Tables 671 and 681.

1.2.4 Condition and Heat Treatment

18% Nickel (250 and 300 KSI) alloys, and 20% nickel alloys are essentially martensitic at room temperature. As mentioned previously, the 25% nickel alloy is largely austenitic at room temperature after solution annealing around 1500°F.

The martensitic alloys can be hardened by maraging the alloys in three different conditions as shown below. In contrast, the 25% nickel alloy can only be heat treated in two conditions and, in order to achieve high strength levels, the alloy must be completely transformed to martensite by a combination of heat treatment before hardening (ausaging) and by maraging. The effect of various heat treating parameters on the mechanical properties and fracture toughness of the various alloys in different conditions are discussed in detail in Section 5.0 of this report. The general summary of the appropriate heat treatment for the various conditions are as follows:

Alloys	Condition	Heat Treatment	Purpose
18% Ni (250) 18% Ni (300) 20% Ni	Annealed	a. Solution anneal at 1400°F-1600°F	Austenitizes, recrystallizes, and solution precipitates
		b. Air Cool	Transforms to martensite
		c. Marage @ 800°F to 950°F	Precipitation hardens and strengthens martensite
18% Ni (250); 18% Ni (300); 20% Ni	"As warm worked"	Marage @ (850°F to 950°F) directly on "hot-rolled" material	Precipitation hardens and strengthens martensite (note simplicity of H.T.)
18% Ni (250) 18% Ni (300) 20% Ni	Cold Worked (moderate percentages)	Marage @ (850°F to 950°F) directly on cold worked material	Precipitation hardens and strengthens martensite
25% Ni	Annealed	a. Solution anneal at 1450°-1600°F	Austenitizes, recrystallizes, and solution precipitates
		b. Ausage @ 1200°F-1300°F	Raises M_s, hardens austenite

Alloys	Condition	Heat Treatment	Purpose
		c. Refrigerate @ -100°F	Transforms to martensite
		d. Marage @ 800°F-950°F	Precipitation hardens and strengthens martensite
25% Ni	Cold Worked	a. Refrigerate @ -100°F	Transforms to martensite
		b. Marage @ 800°F-950°F	Precipitation hardens and strengthens martensite

1.2.5 Melting Methods

Generally, the four alloys should be vacuum-arc-melted to ensure good toughness at high strength levels. The 250 KSI composition has yielded excellent properties from large air melt heats. Extensive work is in progress for the further air melt development of this composition for large solid propellant rocket motor cases.

1.2.6 Primary Working

Ingots should be soaked at 2200°F-2300°F, given an initial breakdown and resoaked for 1½ hours. Subsequent forging should be conducted between 2200°F to 1850°F and hot rolling between 1900°F and 1500°F. A low finishing temperature is recommended for obtaining optimum properties after heat treatment. No problems of cracking at these low temperatures have been encountered.

1.2.7 Corrosion Resistance

1.2.7.1 Corrosion Resistance of Group I (18% Ni) Alloys

Stress corrosion tests conducted in aerated artificial sea water by the International Nickel Company (103) indicate that this group of alloys has good resistance to stress corrosion considering the high strengths involved. The alloys are, however, attacked to some degree.

U-bend test specimens were prepared in the following manner. Strips measuring 1/2 x 1/4 inch were machined in the as-rolled condition and bent through an angle of 150°. Specimens were then maraged in tank argon, cleaned with 300 grit paper, and bent to the final 30°. A total of eight specimens from seven heats, representing yield strengths

ranging from 232,000 to 272,000 psi, have been tested. Results to date are presented in Table 69. As reported, one specimen of 232,000 psi yield strength developed a crack between 92 and 99 days. Two accompanying specimens of 232,000 psi yield strength are unbroken after 120 and 140 days, respectively, although the former, when examined microscopically, exhibited intergranular surface attack.

Four specimens of higher yield strength have shown cracking between 35 and 42 days. Two specimens of this group are unbroken after 82 days.

Microexamination of the broken specimens revealed that the cracks were intergranular in nature. However, the cracks were not of the common hairline type but were rather in the form of a band of some width. A small amount of an intergranular precipitate has been observed; consequently, it is quite likely that the precipitate could contribute to the failure. If the precipitate is directly involved, it is highly possible that stress corrosion resistance can be improved by an adjustment of composition or heat treatment.

Since U-bend specimens obtain a considerable amount of plastic deformation, a complicated stress pattern exists. A simplified stress pattern was studied to more closely approximate loading conditions in structural applications. Two test specimens, 1/16 x 3/16 x 3 inches, were tested under conditions of three-point loading. The load applied was equal to the 0.2 percent yield strength. Simultaneously, for comparative purposes, specimens of quenched and tempered 300-M at a 250,000 psi strength level were also exposed to similar loading. The nickel-cobalt-molybdenum steel specimens have passed 70 days without cracking while the 300-M specimens failed in 2-3 days.

1.2.7.2 Corrosion Resistance of Group 2 (20 & 25% Ni) Alloys

[illegible]e corrosion resistance studies have been performed on the 25% [illegible]ckel alloy by INCO. Three-point loaded stress corrosion tests on material were performed with various boron and zirconium contents. The results are shown below:

Boron and Zirconium Content	0B-0Zn	.002-.01B and/or .02-.05 Zr	.002-.01B and/or .02-.05 Zr
0.2% Yield Strength	220,000 psi	220,000 psi	250,000 psi
Time of Failure	5 heats 1-18 days	5 heats 60 days*	7 heats 60 days*

* Termination of Test

The effect of boron and zirconium additions are self-evident.

U-bend tests in the same environment, however, resulted in failures in less than one day and were independent of boron and zirconium additions. Tests in a salt atmosphere have shown that the general corrosion rate of 25% nickel steels is approximately 0.0005" per year which is approximately one-tenth that of conventional missile steels of the SAE 4130 or 4340 types.

The corrosion resistance of 20% nickel alloy is comparable to that of the 25% nickel alloy.

1.2.8 Welding

Metallurgical behavior of iron-nickel alloy weldments is similar to that of the base material particularly in the Group I Alloys (18% Nickel). The effect of various metallurgical factors on the weld properties of iron-nickel alloys is presented in this section.

International Nickel Co., Inc., introduced welding developments at an early stage of their iron-nickel alloy research program. It was directed for the most part toward welding heavy plate sections, particularly of the 18% nickel type. The results of this work, supplemented by data since obtained by several fabricators, will be reviewed.

1.2.8.1 Group I Alloys (18% Nickel)

Weldability studies conducted on the 18% nickel alloy (250 KSI) demonstrated that weld deposits of essentially matching base metal composition possess both soundness and ability to respond favorably to direct aging treatments specified for base materials (105). This alloy is weldable in both sheet and plate using conventional welding processes. More recent work has demonstrated that the 300 KSI alloy exhibits similar properties in gas, tungsten-arc welded sheet (106).

1.2.8.1.1 Weld and Heat Affected Zone Soundness

Sound, crack-free welds have been obtained in 18% nickel alloy (250 KSI) weldments, in heavy plate sections under conditions of severe restraint (105). Weld deposits in both sheet and plate are relatively free of porosity (105)(107). No evidence of underbead cracking has been observed in the 18% nickel alloy in highly restrained butt welds in fully hardened plate up to 4 inches thick (107). Weldment quality is attained without benefit of a "preheat-interpass-postheat" weld thermal cycle even under the most demanding conditions where heavy sections are welded in the hardened condition (105)(108). To

date, successful plate welding has been achieved using three processes: coated electrode, submerged-arc, and gas metal-arc. In thin sheet sections sound gas, tungsten-arc (TIG) welds have been produced (109).

1.2.8.1.2 Effect of Major Alloying Elements on Weld Strengt' and Soundness

The hardening and transformation mechanisms, and the effect of the various hardening elements on strength, toughness and aging response previously described for base materials in Sections 2.0 and 3.2.1 are essentially the same for weld deposits. Differences which exist are primarily associated with the segregated structure of the cast weld deposit, and to a lesser degree, recovery rates of individual elements.

Early investigations on the effect of various alloying elements on weld strength and toughness were made using coated electrodes (105). The results of this work, were later translated successfully to inert-gas welding, and are believed to be representative of most 18% nickel alloy weldments.

Nickel content, as is the case in base materials, must be controlled within compositional limits. Increasing nickel above 19% in weld deposits results in a sharp decline in notched tensile properties, as well as strength as indicated by hardness, (Figure 144) (105). This effect is attributed to austenite retention, a condition which exists even in 18% nickel weld deposits due to segregation of austenite forming elements. Only limited data is available on the effect of lower nickel contents on weld properties. Work to date has shown that lower nickel levels (16%) enhance notched properties in heavy section weldments, however, only at the expense of weld soundness (105). This improvement is attributed to a more completely martensitic as-welded structure. A loss in weld soundness was not observed in gas tungsten-arc welds in 0.070" sheet made using lower nickel content wires (109). However, it has not been determined that a similar improvement in notched properties over 18% nickel wires is achieved in sheet welds.

Cobalt, molybdenum and titanium are the three basic elements which are varied to obtain the different maraging steel classes (18). Figure 145 shows that increasing molybdenum in a weld deposit first increases strength only at the expense of notched toughness, but with additional amounts the strength also falls off rapidly due to austenite retention (105). This loss in toughness is also observed in base material (Figure 131). A similar effect noted for titanium in the base material (Figure 132) is not as clearly defined in the weld data (Figure 146). However, it would seem that increasing titanium in weld deposits should be controlled to avoid possible adverse retained

austenite effects. Increasing cobalt content increases weld strength (Figure 147) as is the case in base material (Figure 129). Of the three hardening elements, cobalt increases strength with minimum sacrifice to notched strength and danger of retained austenite (105).

As shown in Table 70 (105) 18% nickel weld deposits are prone to severe weld porosity in the absence of titanium and/or aluminum. Titanium and aluminum in addition to any beneficial hardening effects act as gas fixing agents in the weld deposit. In coated electrode core wires titanium is also necessary to control weld cracking (Table 70). When added in sufficient amounts, titanium eliminates weld cracking.

1.2.8.1.3 Effect of Residual Elements

Control of residual elements known to have adverse effects on the base material properties is particularly critical in welds because of inherent segregation. Carbon, manganese, phosphorus, and sulfur should be controlled within limits specified for base materials in Section 3.2.2 (110). Data on the effect of increasing manganese content in weld deposits is shown in Figure 146 (105). Weld strength is reduced considerably due to austenite retention.

Insufficient data is available to evaluate the effect of silicon on weld properties. Data obtained on coated electrode deposits indicate that the deleterious effect of silicon in base materials is not as pronounced in welds (105).

Aluminum in the amounts added in the base material for deoxidation purposes is not detrimental to weld properties. Residual aluminum supplements titanium in controlling weld porosity (105).

Boron and Zirconium. The effects of small additions of boron and zirconium on weld properties are not well established. To date, no detrimental effect has been noted in welds made in thin sheet using filler wires containing boron and zirconium (Table 71) (109) (111).

1.2.8.1.4 Heat Treatment

The weld and heat-affected-zone of the 18% nickel alloy responds to normal base material maraging treatments (105) (107).

The effect of maraging temperature on the hardening response of a 200 KSI weld deposit is shown in Figure 148 (105). A similar behavior would be expected in 250 and 300 KSI welds. Initial weld hardening begins at about 700°F, as is the case with base materials.

The heat affected zone of solution heat treated material is hardened somewhat in the area exposed to maraging temperatures, but aging at 900°F equalizes hardness between heat-affected-zone and unaffected base metal (105) (107). The heat-affected-zone of fully heat treated material is softened during welding to its annealed hardness. Re-hardening of this zone is accomplished by reheating at about 900°F as shown in Figure 149 (110) which demonstrates the ability of 18% nickel steel weldments to respond to local post weld heat treatment.

It is known that exposure of the 18% nickel alloys to temperatures in the 1200 to 1300°F range results in austenite stabilization and incomplete maraging response (112). This effect is experienced in weld heat-affected-zones exposed to stabilization temperatures, but does not appear to be pronounced. It is reflected as a slight loss in hardness after aging in a narrow band of the heat-affected-zone. To date, this behavior has not been found to be detrimental to weld tensile properties, Table 71 (109) (111).

As shown in Tables 71 and 72 welds made using various welding processes are hardened by normal base material maraging treatments at 900°F (105) (109). Sheet welds which were solution heat treated at 1500°F prior to maraging failed to show any superiority in tensile properties over directly maraged welds (Table 69).

1.2.8.1.5 Composition Specifications

Filler wires for inert-gas welding should be of essentially matching base metal composition. Present coated electrode core wires and submerged-arc filler wire compositions are titanium-modified versions which deposit matching base metal compositions. Currently INCO recommends that boron, zirconium and calcium additions be excluded from weld wires since it has not been shown that these additions are essential to fracture toughness.

On the basis of data available to date, the recommended composition specifications for inert-gas filler wires are as given in Table 73 (105) (110). Coated electrode core wire and wire for submerged-arc welding are essentially the same except for titanium which is increased to 2.0-2.5 percent (105) (110).

1.2.8.1.6 Melting Method

Filler wires for inert-gas welding must be vacuum-melted, and it is advisable to use the purest melting stock obtainable (110). Vacuum-melting is desirable not only to insure maximum weld notched toughness but also to obtain adequate weld soundness particularly in welding heavy sections. Instances of transverse weld cracking have been

experienced in gas metal-arc welds made in heavy plate using air melted wires (105). Vacuum-melting is also recommended for coated electrode and submerged-arc welding wires (110).

1.2.8.2 Group II Alloys (20 and 25% Nickel)

The 20 and 25% nickel alloys are weldable in sheet form using the gas tungsten-arc process (107 (108) (109). Work completed to date indicates that use of modified matching base material filler wires is preferred for welding to obtain a maximum balance of weld strength and toughness (110) (111). Welding of the 20 and 25% nickel alloys in plate form has been relatively limited. Currently, a filler wire of 18% nickel alloy is recommended for welding these alloys in plate sections (109).

1.2.8.2.1 Weld and Heat Affected Zone Soundness

No evidence of underbead cracking has been observed in the 20 and 25% nickel alloys even in butt welds made in heavy plate sections (114) (115). It has also been reported that sound, crack-free welds could be produced in 20 and 25% nickel butt welds in plate sections (115). Welds demonstrated freedom from porosity and were made without a "preheat-interpass-post heat" weld thermal cycle. Plate welds in 20% and 25% nickel alloy have been made using gas tungsten-arc, gas metal arc and coated electrode processes (115).

1.2.8.2.2 Effect of Major Alloying Elements on Weld Strength and Soundness

The hardening and strengthening mechanism in the Group II alloys welds is essentially the same as that described for the base materials in previous Sections 1.1 and 1.2.2.4.

No published data is available on the effect of the major alloying elements, titanium and aluminum, on weld properties. However, the effects noted for the base materials in Section 1.2.2.4 are expected to be reflected in welds of similar composition. Weld segregation and hardness recovery rates should be considered in any translation of these data to welds.

Early work suggested that modifying the 20% nickel filler wires by lowering the nickel content and adding molybdenum would be useful in improving weld notched toughness (109) (111).

The lower nickel content was intended to insure a more completely martensitic structure as-deposited. Molybdenum was added to improve ductility and toughness. Additions of molybdenum, a potent austenite

former, are limited to about 1.5 to 1.7% in order to maintain a proper balance of composition without upsetting the transformation characteristics of the alloy system (111).

Titanium and aluminum, the major alloy hardeners, also act as gas fixing elements which control porosity.

1.2.8.2.3 Effect of Residual Elements

The Group II Alloy residual elements listed in Section 1.2.2.5 should be controlled in welds within the limits specified for base materials.

Specific data on the effect of residual elements on properties of 20 and 25% nickel alloy welds is not available. However, similar if not more adverse behavior than is experienced in base materials is expected in high strength weld deposits due to segregation tendencies. This is particularly true of elements such as manganese, silicon, phosphorus and sulfur which are known to either promote austenite retention or lower ductility and notched toughness in 20 and 25% nickel alloys.

Boron and Zirconium. The need for boron and zirconium in weld deposits is not well established. To date, no detrimental effects have been observed in sheet welds made using filler wires containing boron and zirconium (114).

1.2.8.2.4 Heat Treatment

The weld and heat-affected-zone of the 20% nickel steel alloys respond to direct maraging treatments normally used for base materials, (109) (110) (115).

Like the 18% nickel steel the heat-affected-zone is hardened in the area exposed to maraging temperatures. Maraging at 850°F equalizes hardness between heat-affected-zone and unaffected base metal. Preliminary tensile data obtained on welded 20% nickel alloy sheet indicated that weld deposits respond to direct maraging treatments, Table 74 (107) (109).

Solution heat treated 25% nickel alloy is hardened slightly in the area of the weld heat-affected-zone exposed to ausaging temperatures (110). A complete heat treatment cycle; i.e., ausage, refrigerate, and marage, equalizes hardness between heat-affected-zone and unaffected base metal. (Figure 150). The weld heat-affected-zone also responds to refrigeration and marage treatments to about the same degree as does unaffected base material as shown in Figures 151 and 152. These hardness surveys also illustrate the need for ausaging and refrigeration of weld deposits to obtain comparable base

metal hardness. A complete heat treatment cycle was found necessary even when 20% nickel alloy filler wires were deposited on 25% nickel base metal (Figure 151).

Recent work (114) has shown that aged 20% nickel alloy sheet weld tensiles often experience premature failure accompanied by a loss in ductility. Failure is localized in the weld heat-affected-zone. The nature of this embrittlement is not known. Preliminary weld tests conducted by INCO (109) did not reveal this behavior.

Tensiles from welds in ½-inch thick 20% nickel alloy plate were found free of any heat-affected-zone embrittlement after heat treatment (114).

1.2.8.2.5 Composition Specifications

Welding of 20 and 25% nickel alloys has been limited for the most part to inert-gas welding. Filler wire compositions are not as yet set. Currently, INCO recommends that molybdenum-modified filler wires of essentially matching base metal composition be used (110). As in the case of the 18% nickel filler wires, exclusion of boron, zirconium and calcium additions is advised at this time (110).

On the basis of data available to date, the recommended composition specification for inert-gas filler wires are given in Table 75. It should be noted that the 18% nickel alloy filler wires are also suggested for welding 20 and 25% nickel (109).

1.2.8.2.6 Melting Method

Filler wires for inert-gas welding must be vacuum-melted, and it is advisable to use the purest melting stock available (110).

EFFECT OF MOLYBDENUM & MOLYBDENUM + COBALT ON HARDNESS OF 18.5-20.1 NI, BAL. FE ALLOYS.

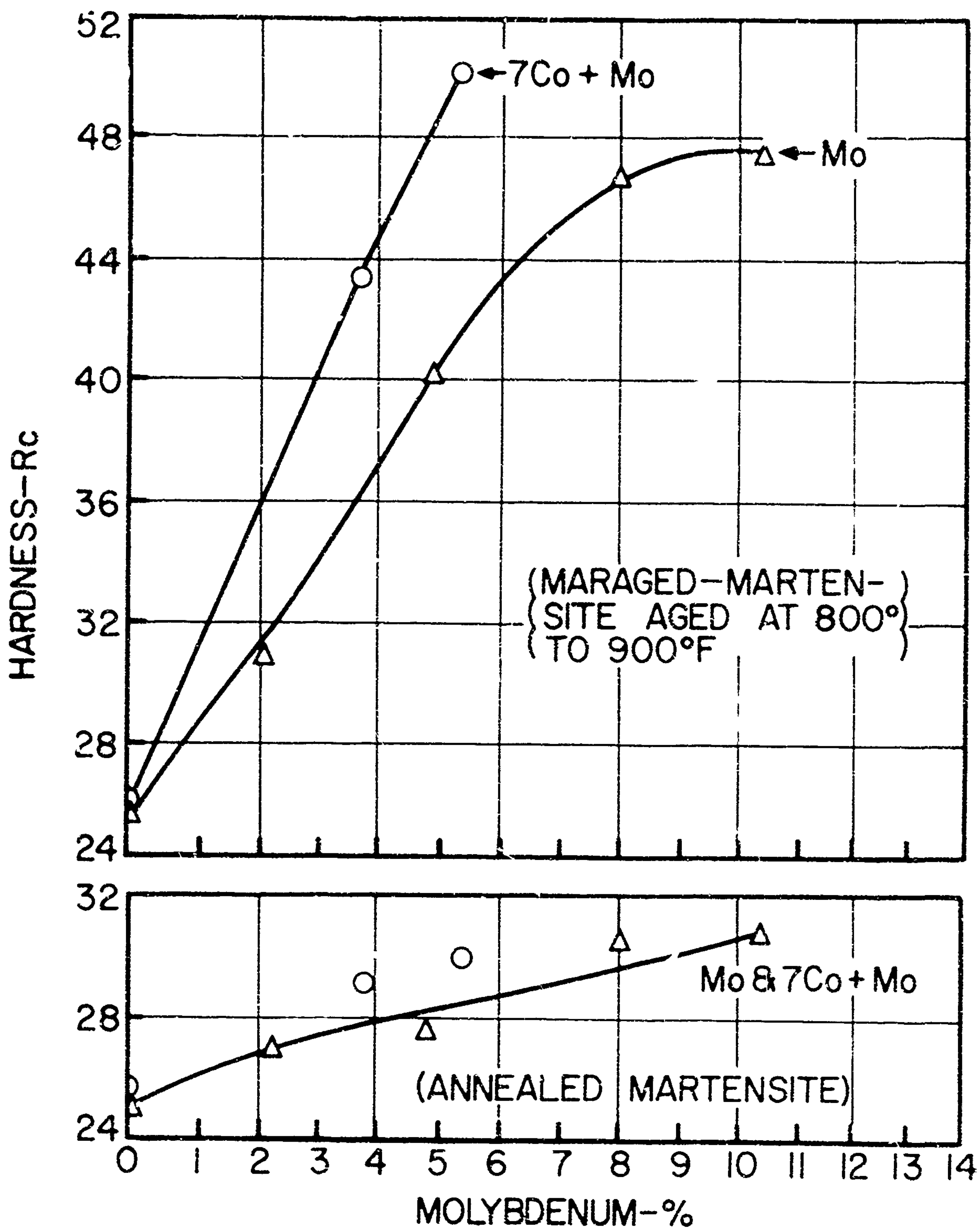


Figure 128

EFFECT OF COBALT X MOLYBDENUM PRODUCT ON HARDNESS
OF 18 5-20.1 NI., BAL. FE ALLOYS

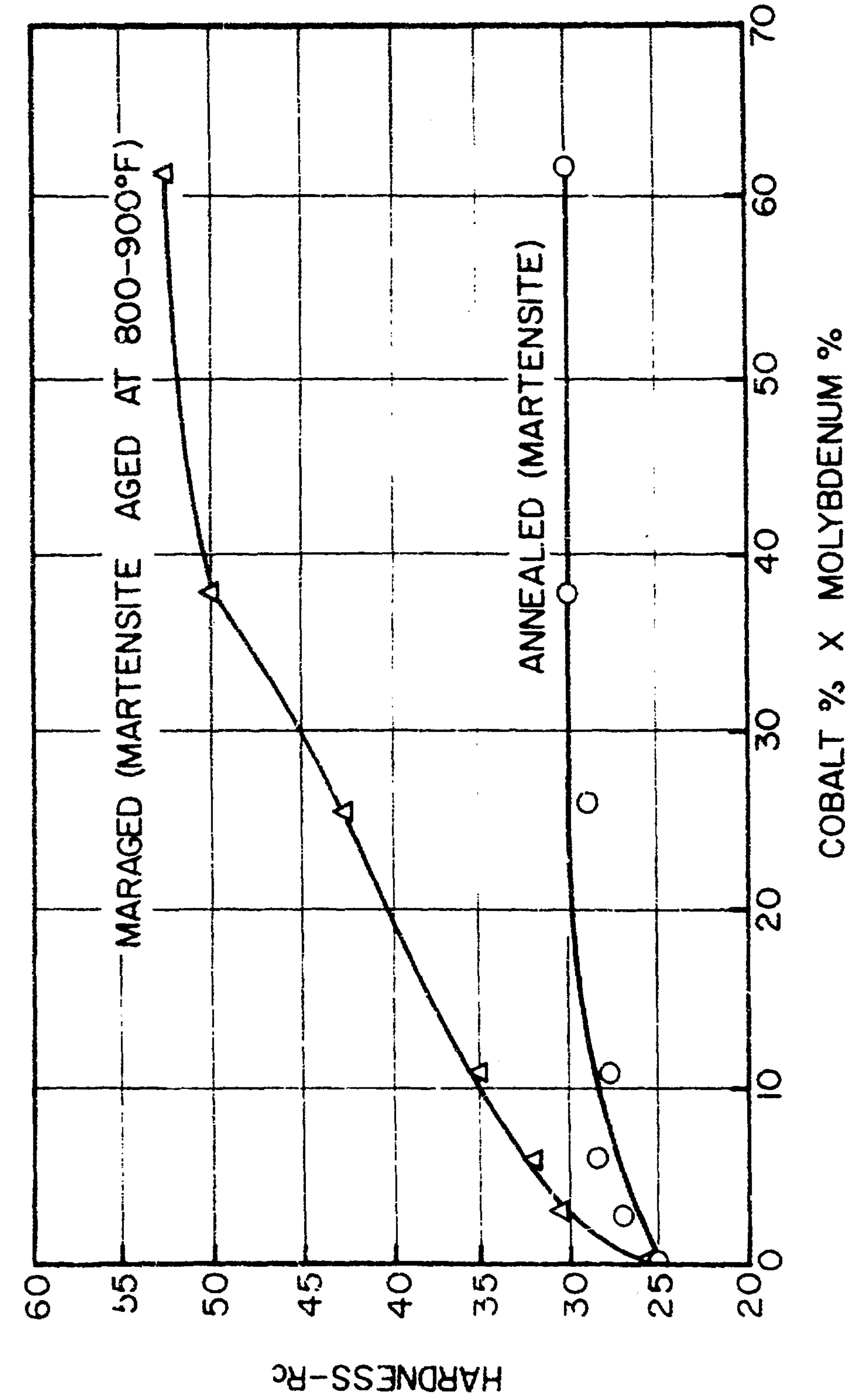


Figure 129

EFFECT OF MOLYBDENUM ON YIELD STRENGTH AND NTS/TS OF 18.5 NI., 7.5 CO, 0.4 TI, BAL. FE, 30 LBS. AIR MELTS

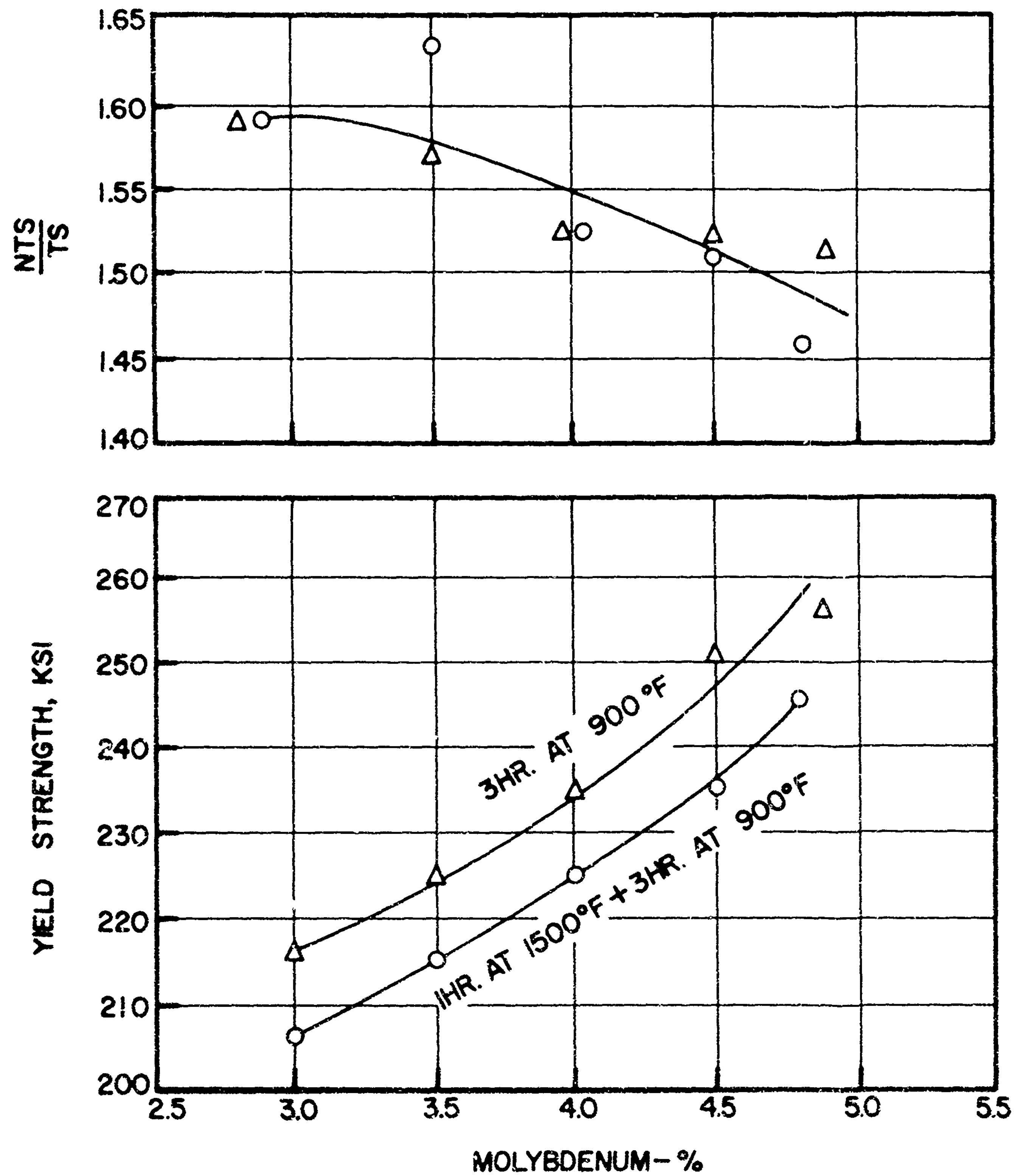


Figure 130

EFFECT OF COBALT & MOLYBDENUM ON YIELD STRENGTH & NOTCHED TENSILE STRENGTH (0.5" MAJ. DIA. ROUND) OF 18.5 NI., BAL. FE, 30LBS AIR MELTS. ANNEALED + 3HRS AT 900° F

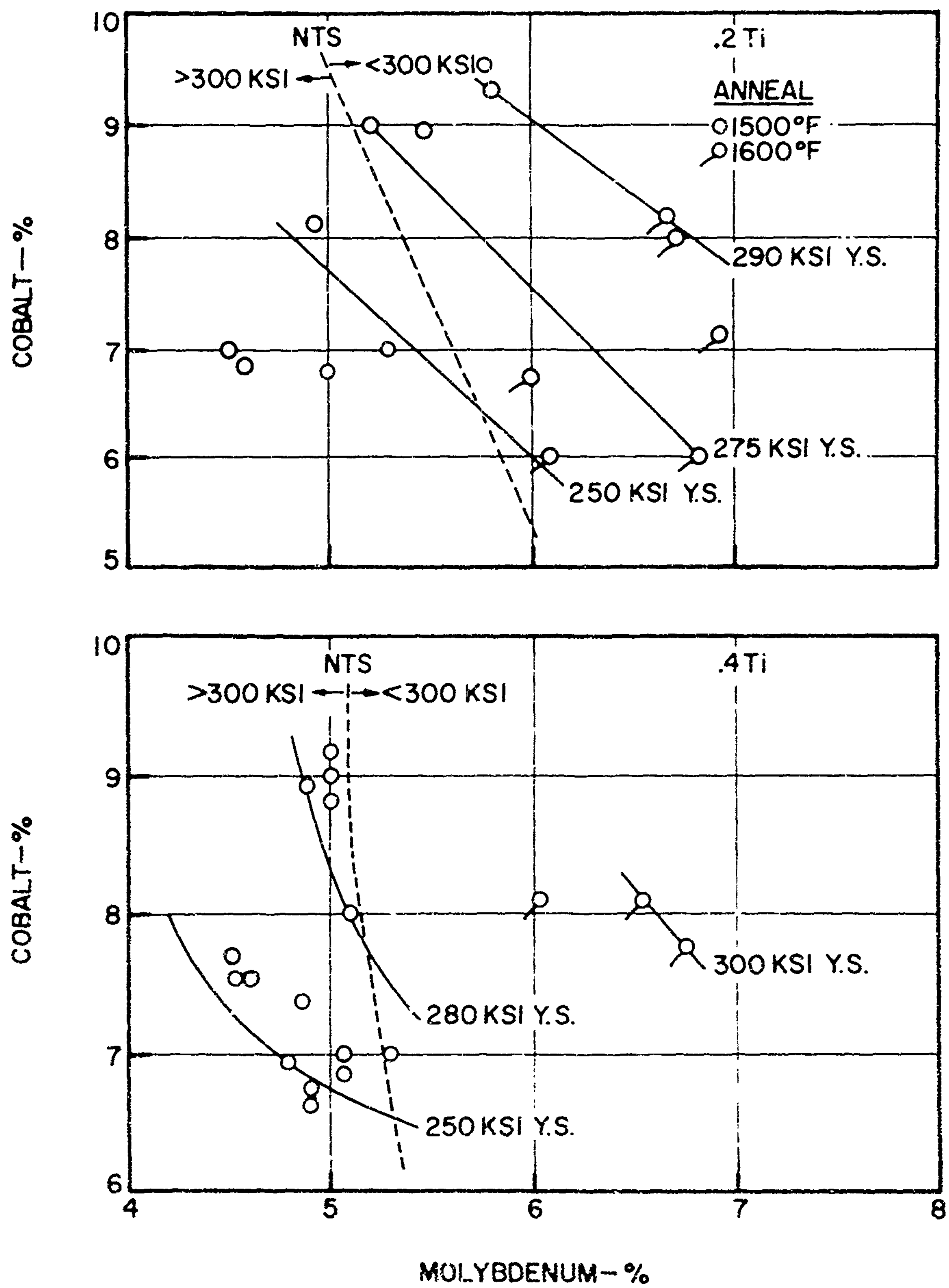


Figure 131

EFFECT OF TITANIUM ON THE PROPERTIES OF THE 18 NI-7 CO-5 MO STEEL

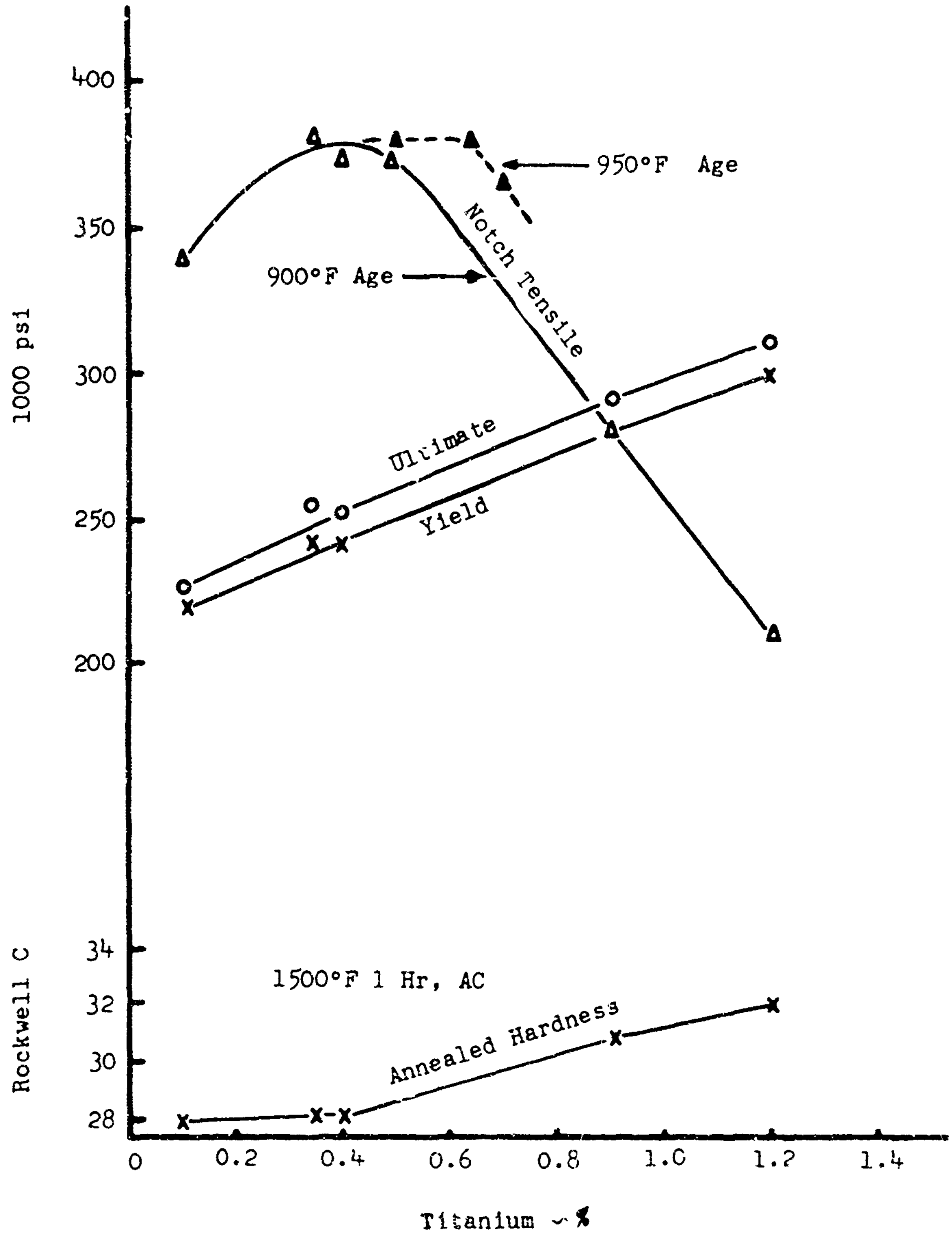


Figure 132

EFFECT OF TITANIUM ON YIELD STRENGTH & NTS/TS
0.` 18.5 NI, 7-7.5 CO, 5 MO, BAL. FE, 30 LBS MELTS.
ANNEALED 1HR. AT 1500°F PLUS MARAGE

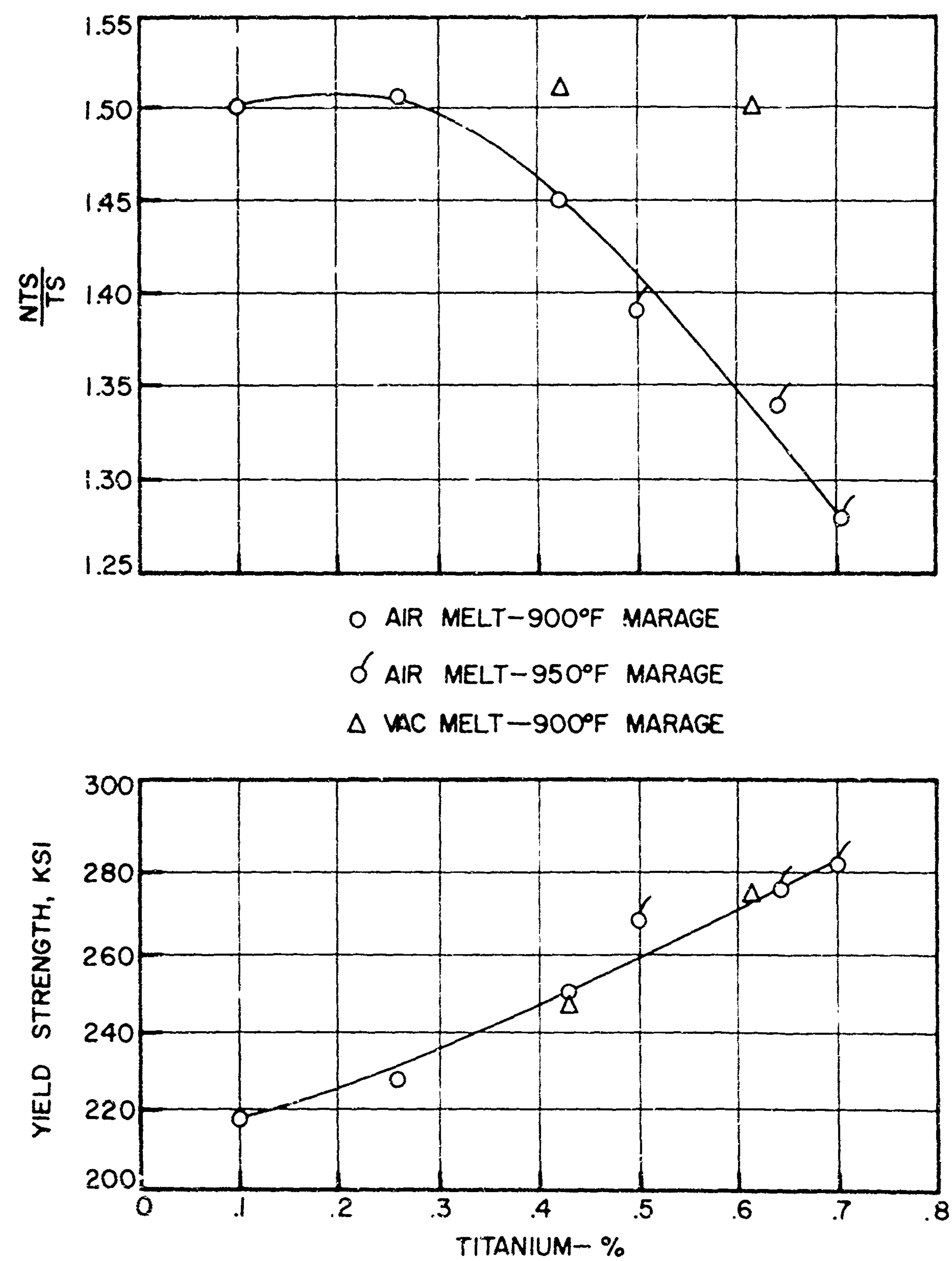


Figure 133

EFFECT OF CARBON CONTENT ON STRENGTH &
TOUGHNESS OF THE 18.5NI, 7-7.5CO, 5MO ALLOY

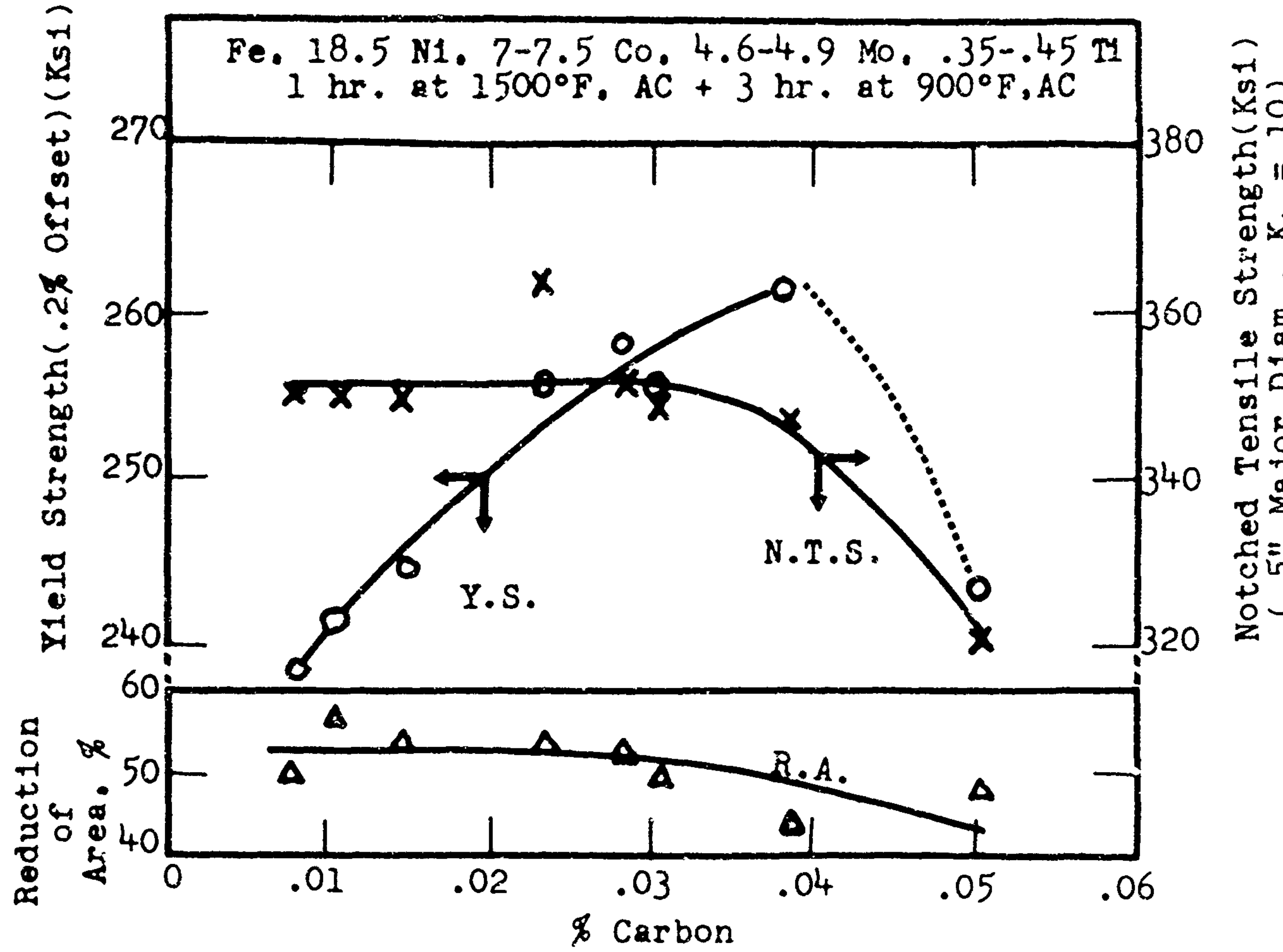
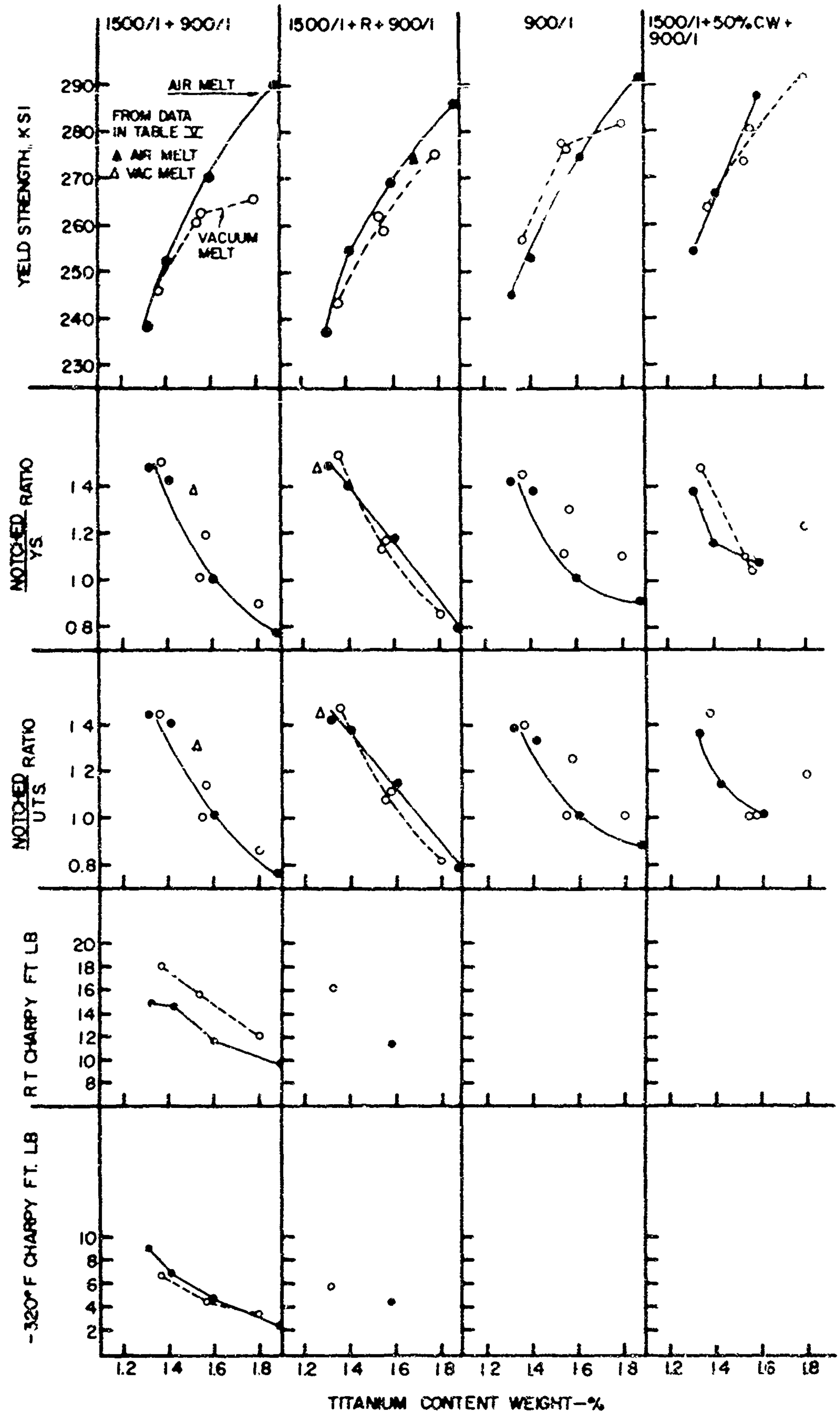


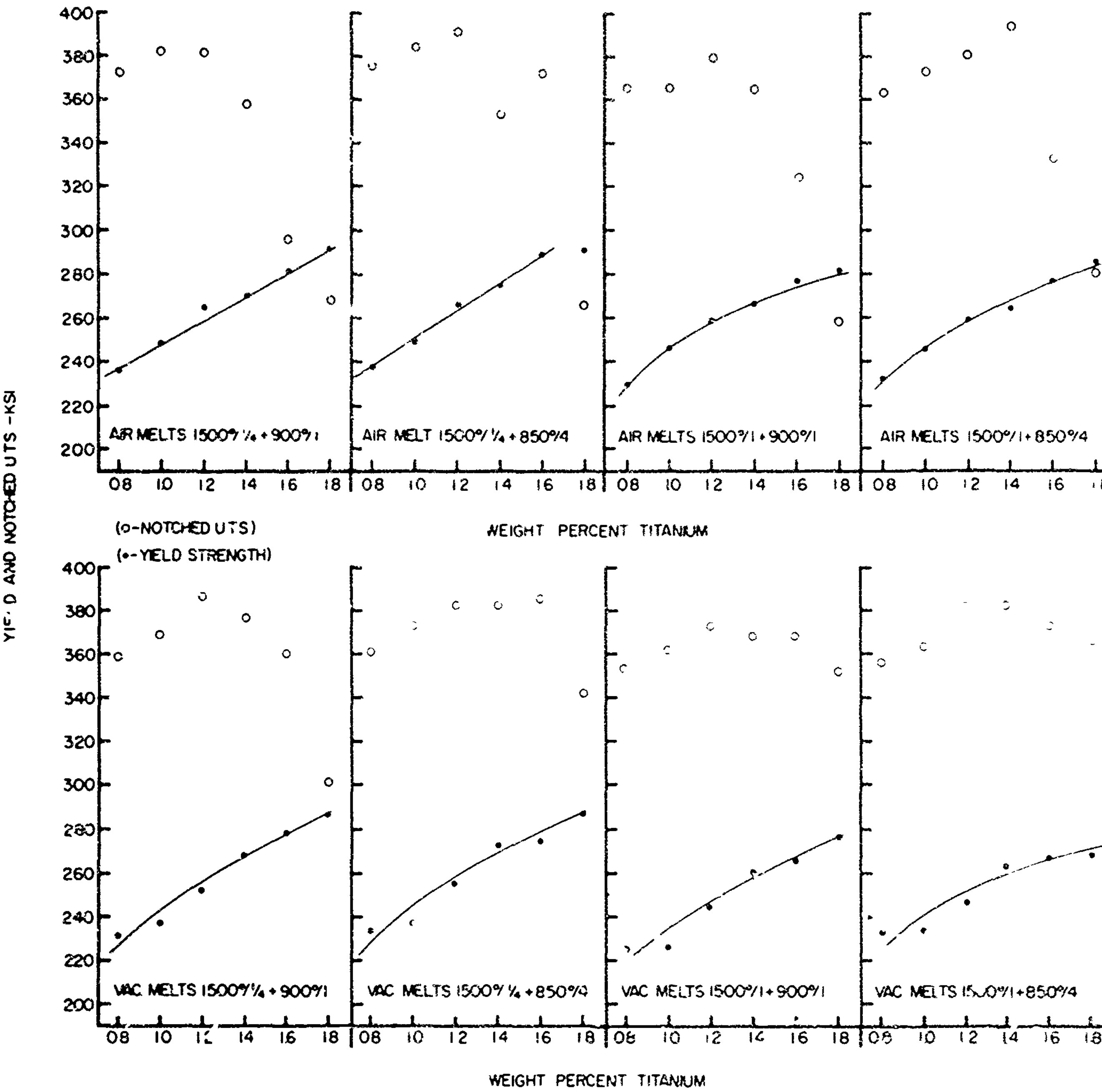
Figure 134

3436



GRAPHIC REPRESENTATION OF MECHANICAL PROPERTIES OF AIR AND VACUUM MELTED 20% NICKEL ALLOY.

Figure 135



ROOM TEMPERATURE YIELD STRENGTH AND NOTCHED TENSILE STRENGTH FOR [illegible]0% NICKEL STEEL AIR AND VACUUM MELTS AFTER VARIOUS HEAT TREATMENTS

Figure 136

3430

EFFECT OF TITANIUM CONTENT ON THE STRENGTH, DUCTILITY AND NOTCH PROPERTIES OF THE 25% NICKEL ALLOY

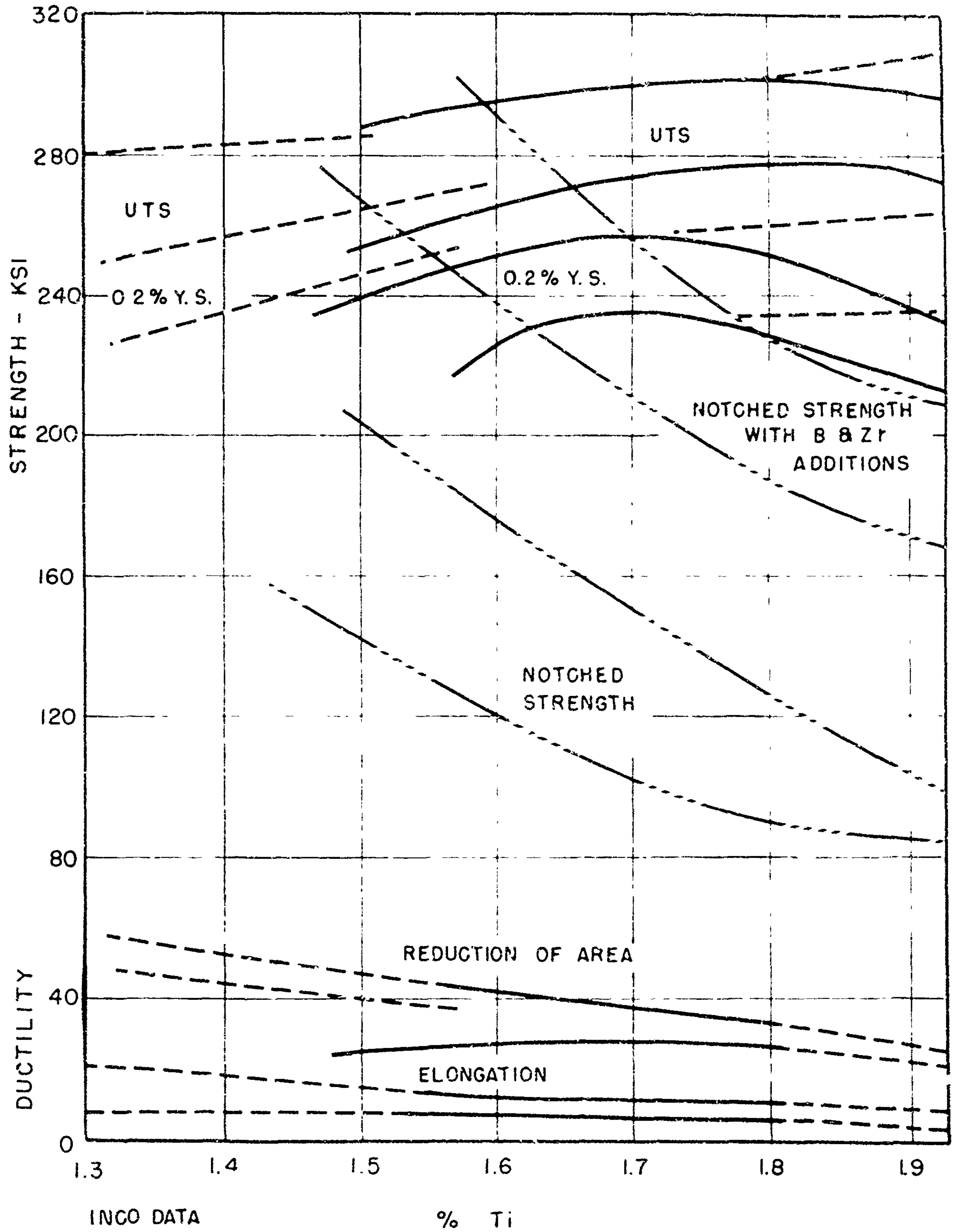


Figure 137

3435

THE EFFECT OF BORON AND ZIRCONIUM ON THE NOTCH STRENGTH OF THE 25% NICKEL ALLOY

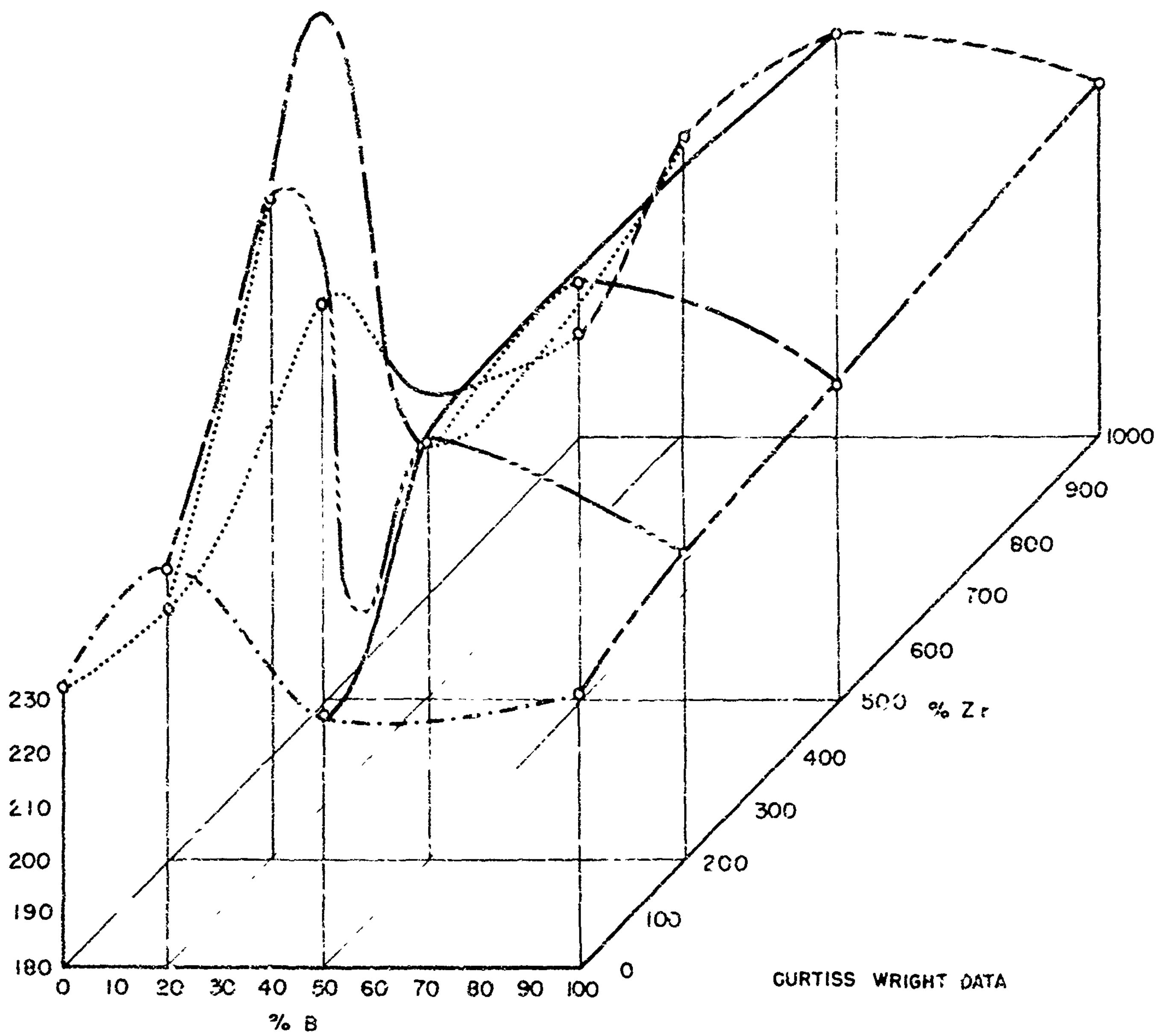


Figure 138

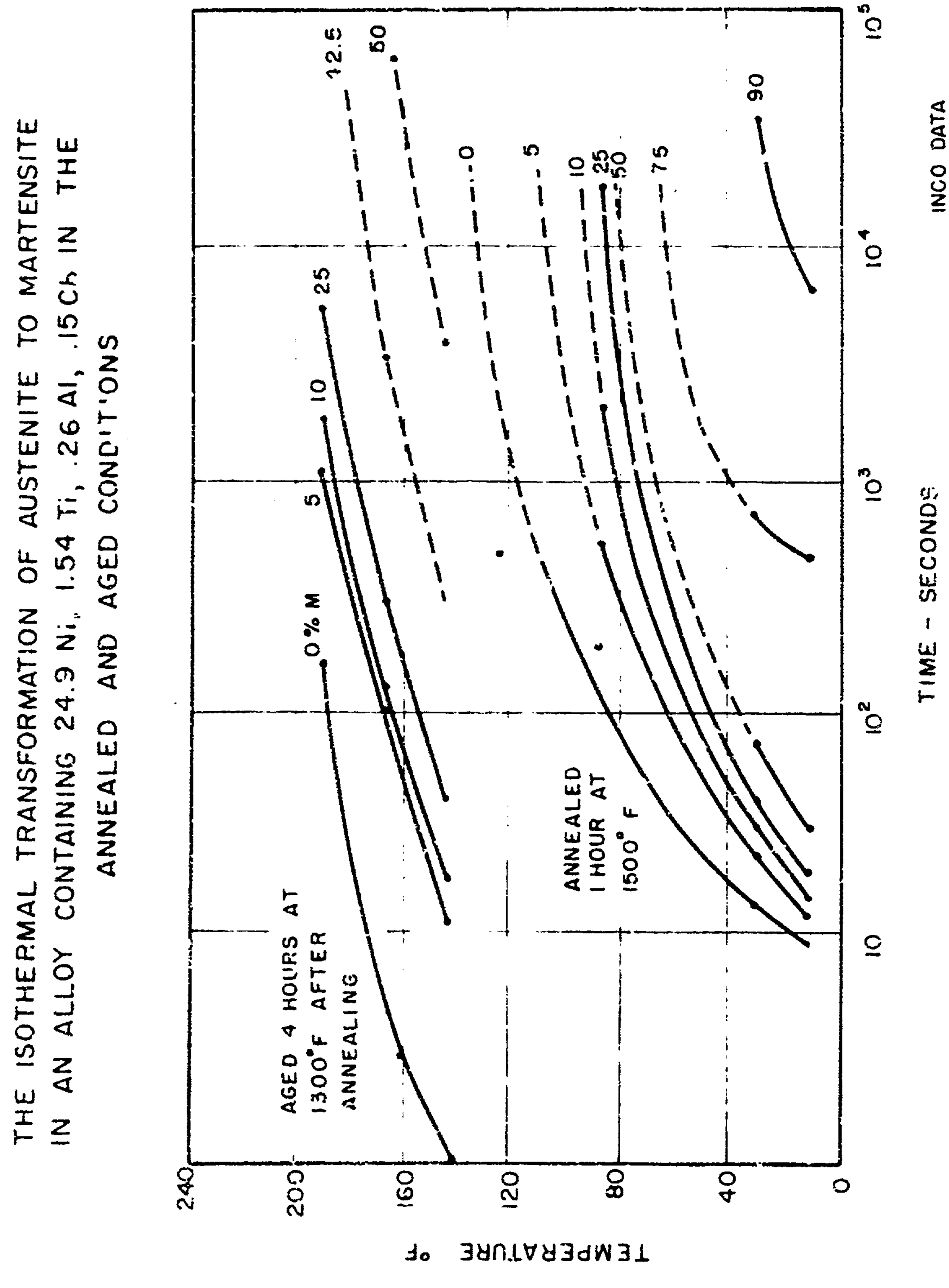
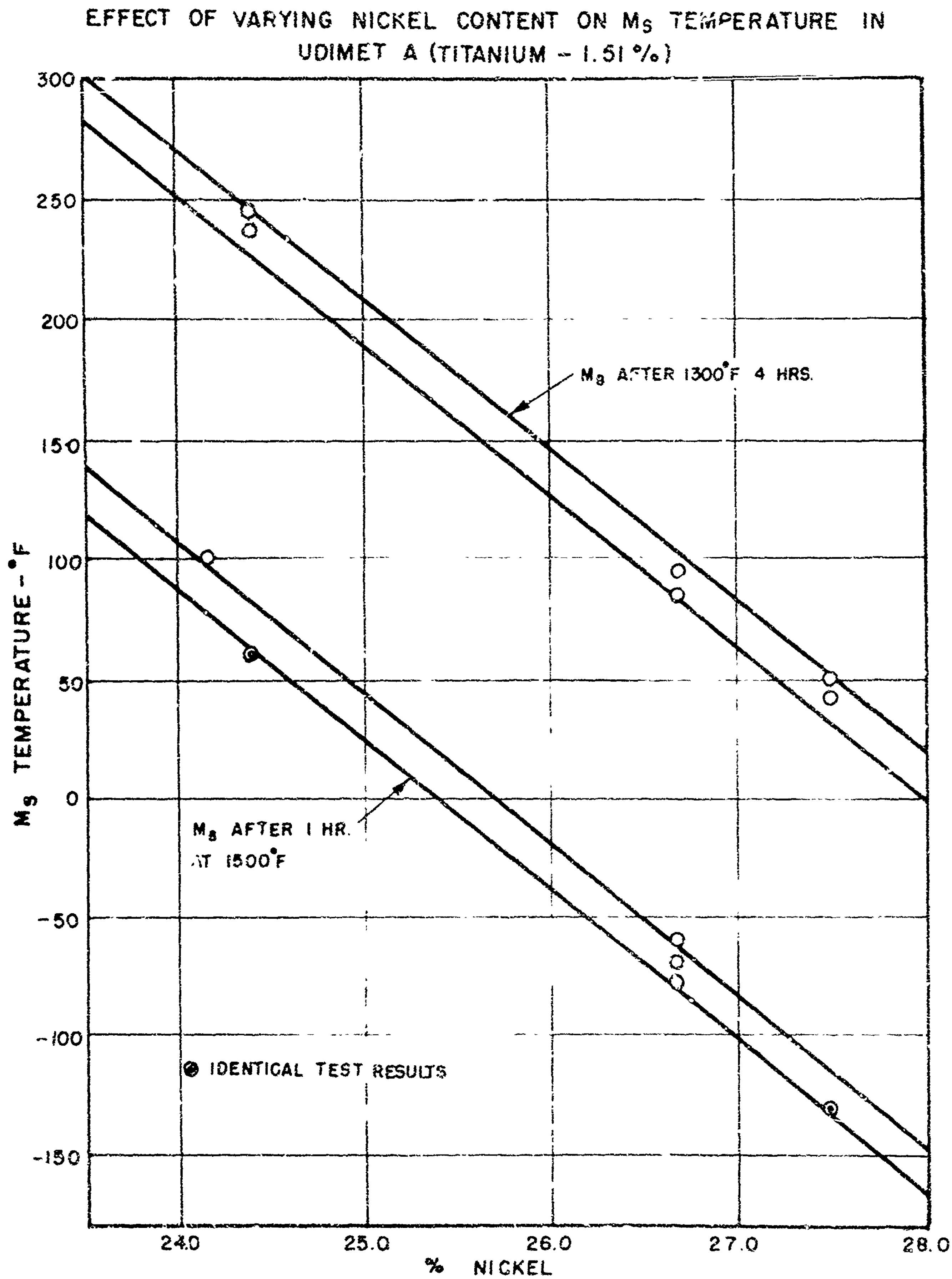

THE ISOTHERMAL TRANSFORMATION OF AUSTENITE TO MARTENSITE
IN AN ALLOY CONTAINING 24.9 Ni, 1.54 Ti, .26 Al, .15 Cb IN THE
ANNEALED AND AGED CONDITIONS
AGED 4 HOURS AT
1300°F AFTER
ANNEALING
ANNEALED
1 HOUR AT
1500° F
0 % M
5
10
25
12.5
50
0
5
10
25
50
75
90
TEMPERATURE °F
240
200
160
120
80
40
0
10
10^2
10^3
10^4
10^5
TIME - SECONDS
INCO DATA

Figure 139



EFFECT OF VARYING NICKEL CONTENT ON M_S TEMPERATURE IN UDIMET A (TITANIUM - 1.51 %)
300
250
200
150
100
50
0
-50
-100
-150
M_S TEMPERATURE - °F
M_S AFTER 1300°F 4 HRS.
M_S AFTER 1 HR. AT 1500°F
IDENTICAL TEST RESULTS
24.0
25.0
26.0
27.0
28.0
% NICKEL

Figure 140

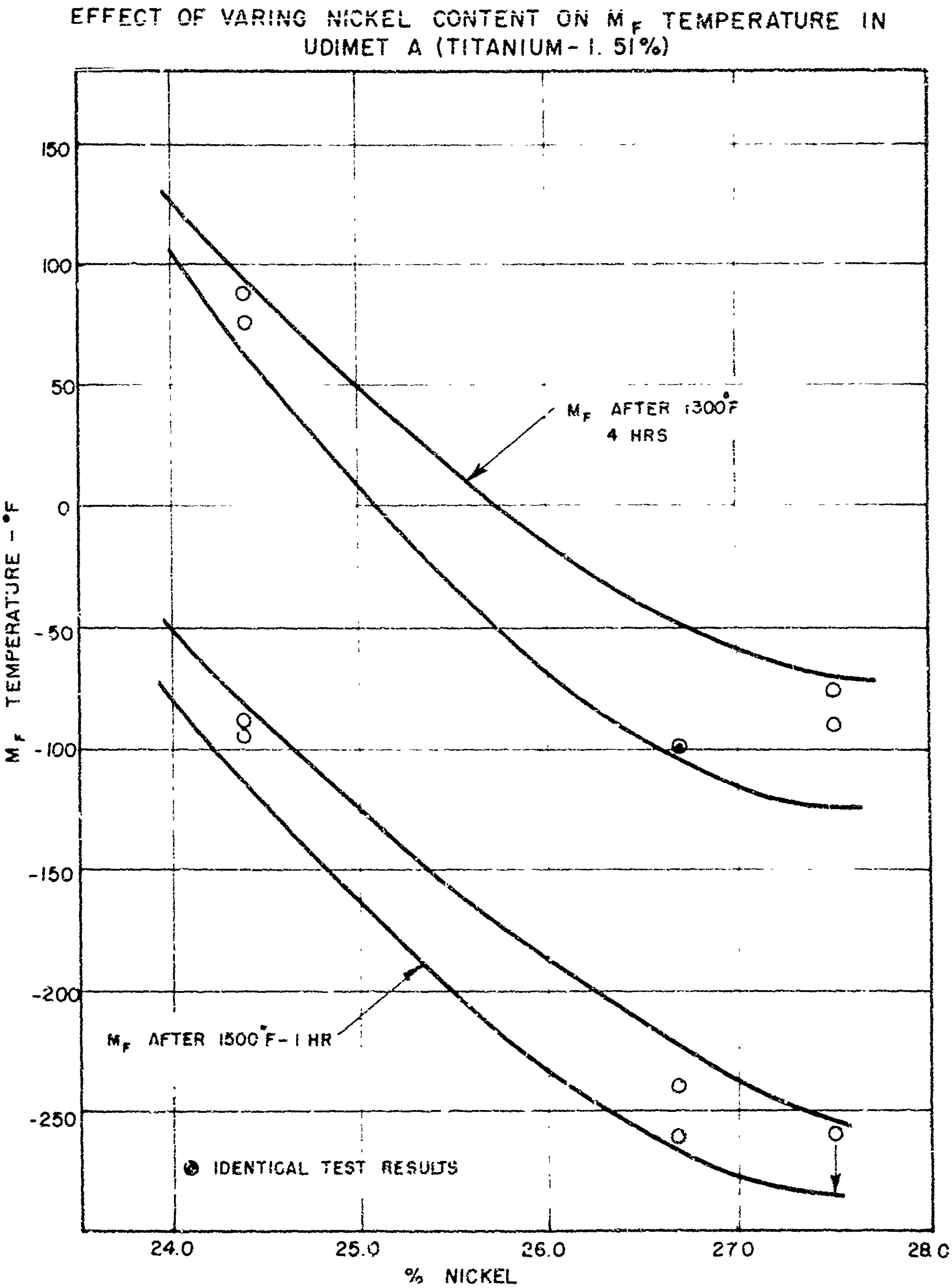

EFFECT OF VARING NICKEL CONTENT ON M_F TEMPERATURE IN UDIMET A (TITANIUM - 1.51%)
M_F TEMPERATURE - °F
150
100
50
0
-50
-100
-150
-200
-250
M_F AFTER 1300°F 4 HRS
M_F AFTER 1500°F - 1 HR
IDENTICAL TEST RESULTS
24.0
25.0
26.0
27.0
28.0
% NICKEL

Figure 141

EFFECT OF VARYING TITANIUM CONTENT ON M_S TEMPERATURE IN UDIMET A (NICKEL - 25.70 %)

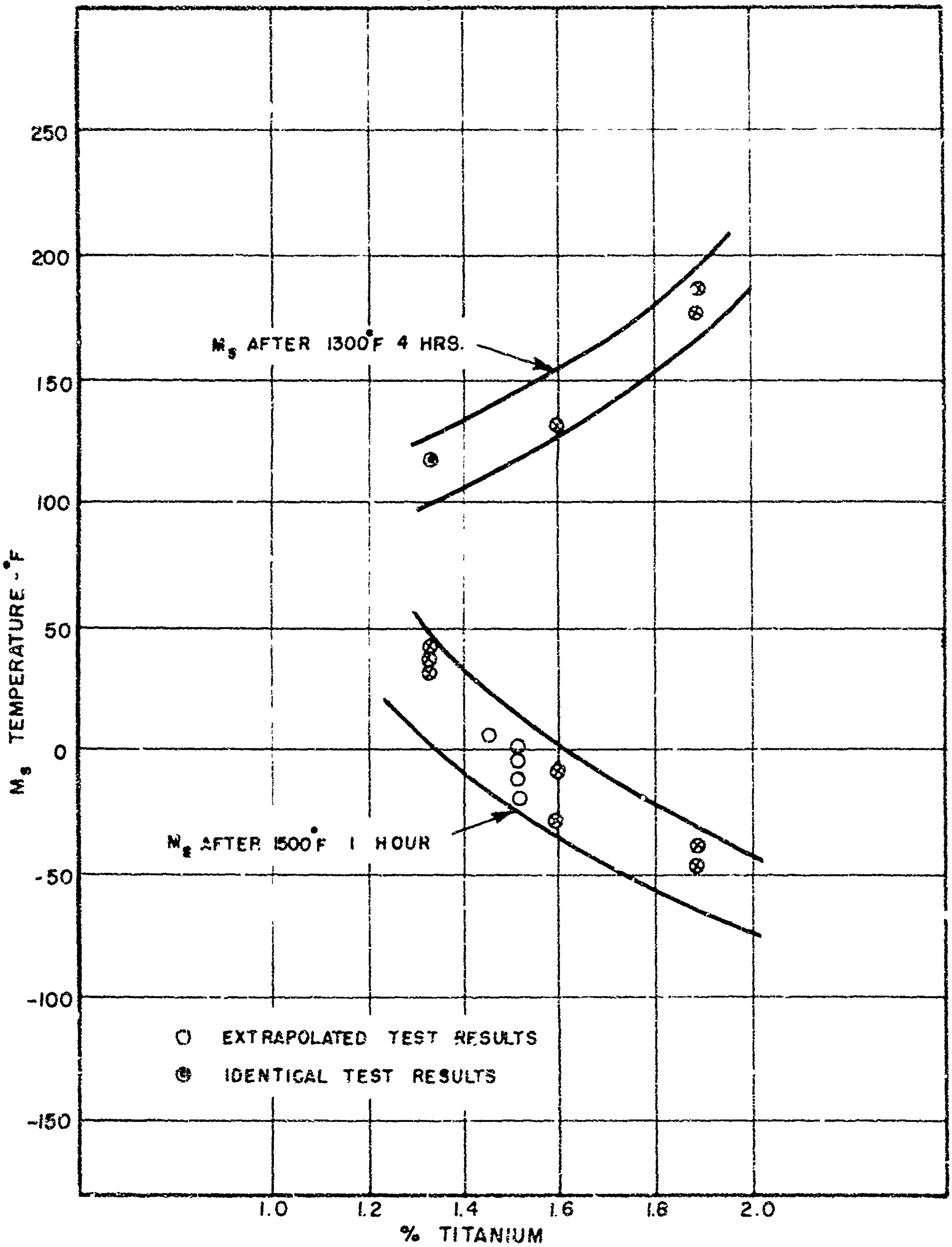


Figure 142

EFFECT OF VARYING TITANIUM CONTENT ON M_F TEMPERATURE IN UDIMET A (NICKEL - 25.70 %)

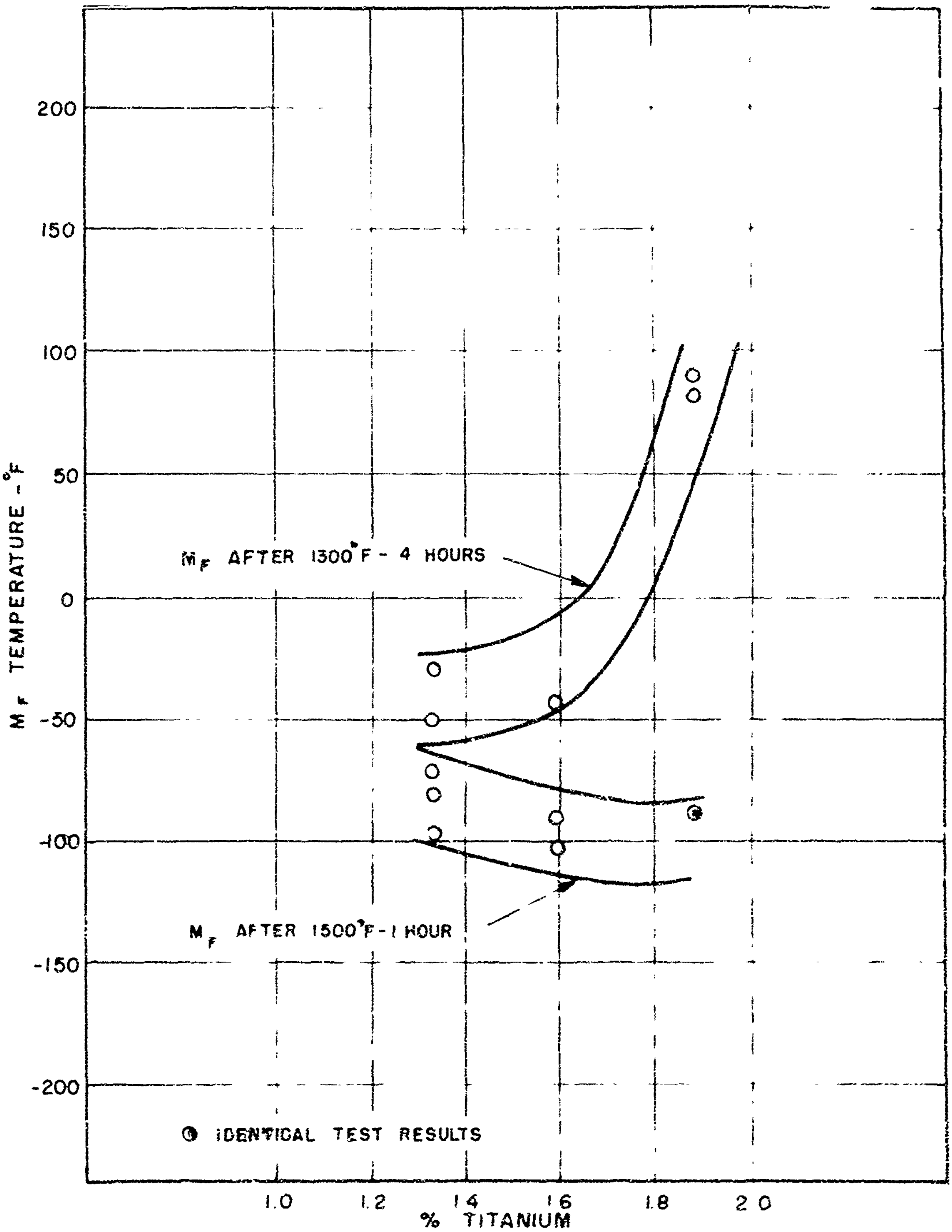


Figure 143

342

EFFECT OF NICKEL ON TRANSVERSE WELD PROPERTIES
18% Ni STEEL (250 KSI) - COATED ELECTRODE DEPOSITS

MARAGED: 900°F/3 Hrs.

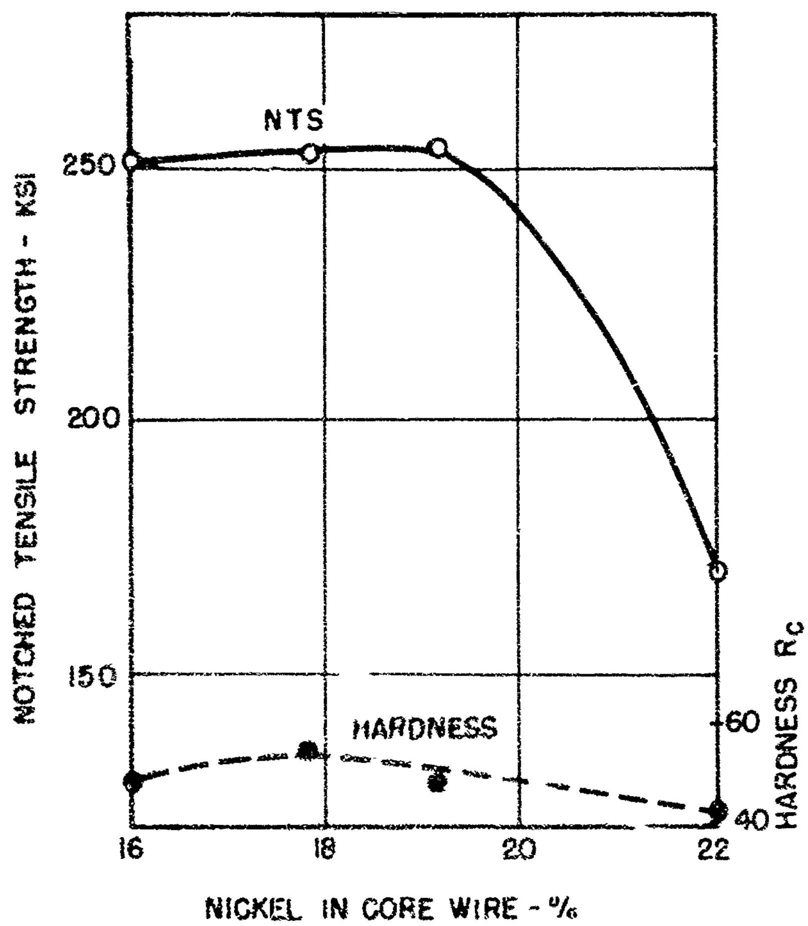


Figure 144

3863

EFFECT OF MOLYBDENUM ON TRANSVERSE WELD PROPERTIES
18% NICKEL (250 KSI) - COATED ELECTRODE DEPOSITS

MARAGED: 900°F/3 Hrs.

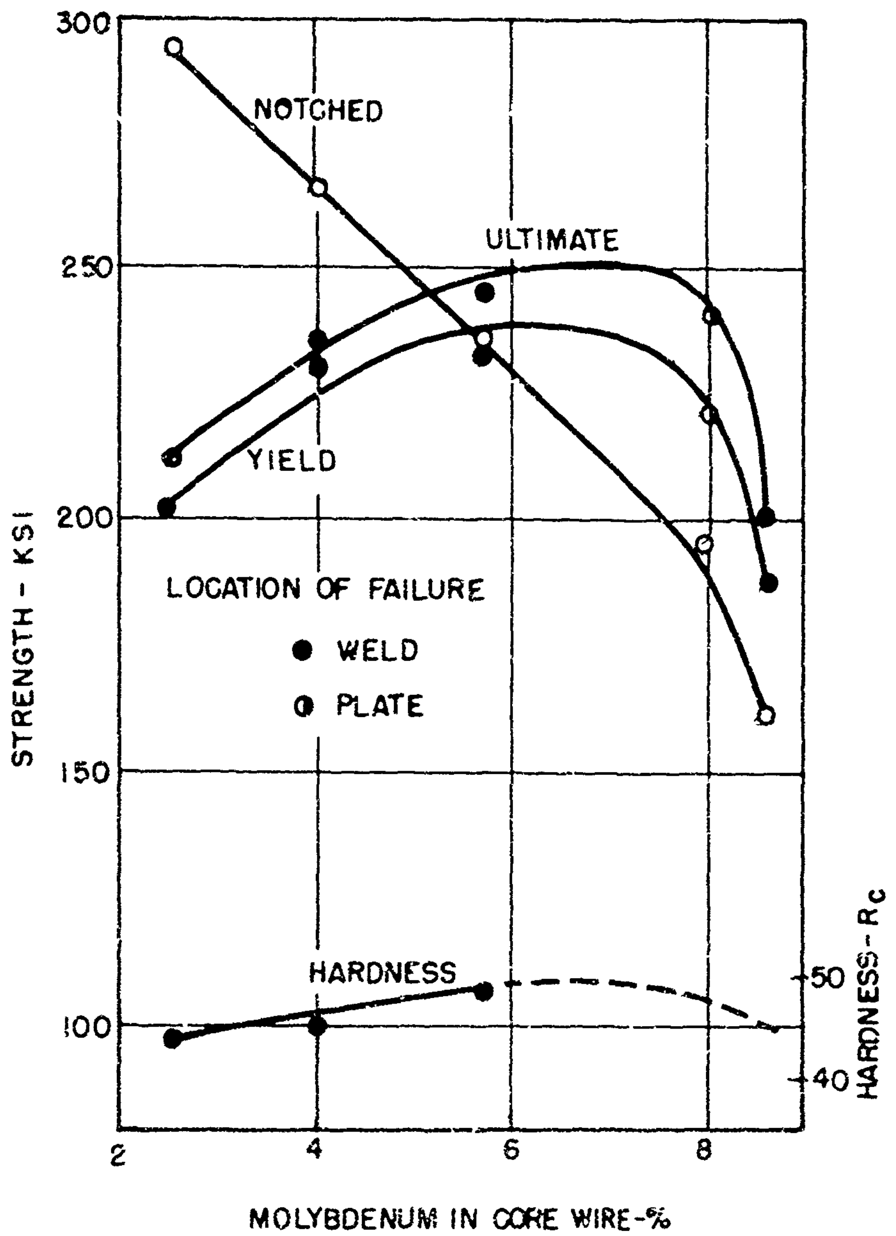
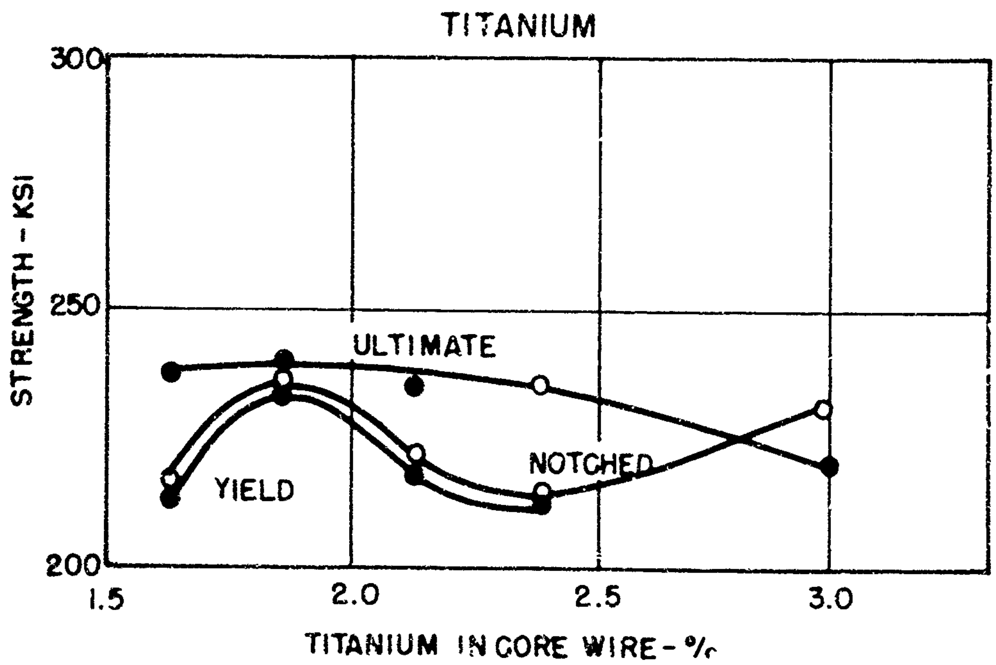


Figure 145

EFFECT OF COMPOSITION ON TRANSVERSE WELD PROPERTIES
18% NICKEL (250 KSI) - COATED ELECTRODE DEPOSITS

MARAGED: 900°F/3 Hrs.



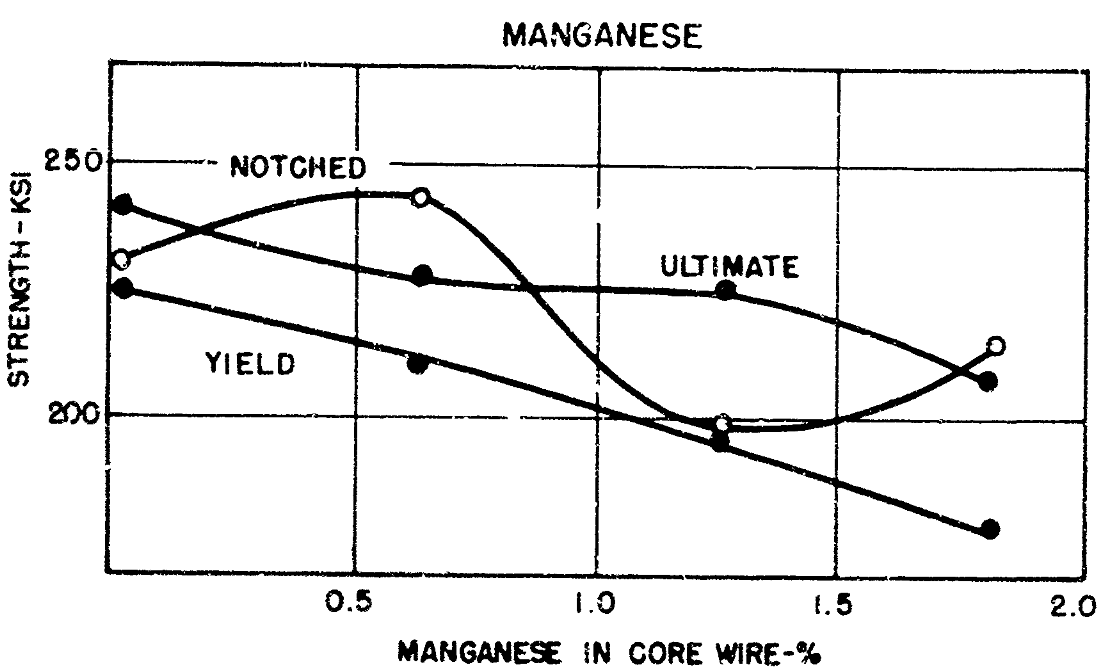


Figure 146

3863

EFFECT OF COBALT ON TRANSVERSE WELD PROPERTIES
18% NICKEL (250 KSI) - COATED ELECTRODE DEPOSITS

MARAGED: 900°F/3 Hrs.

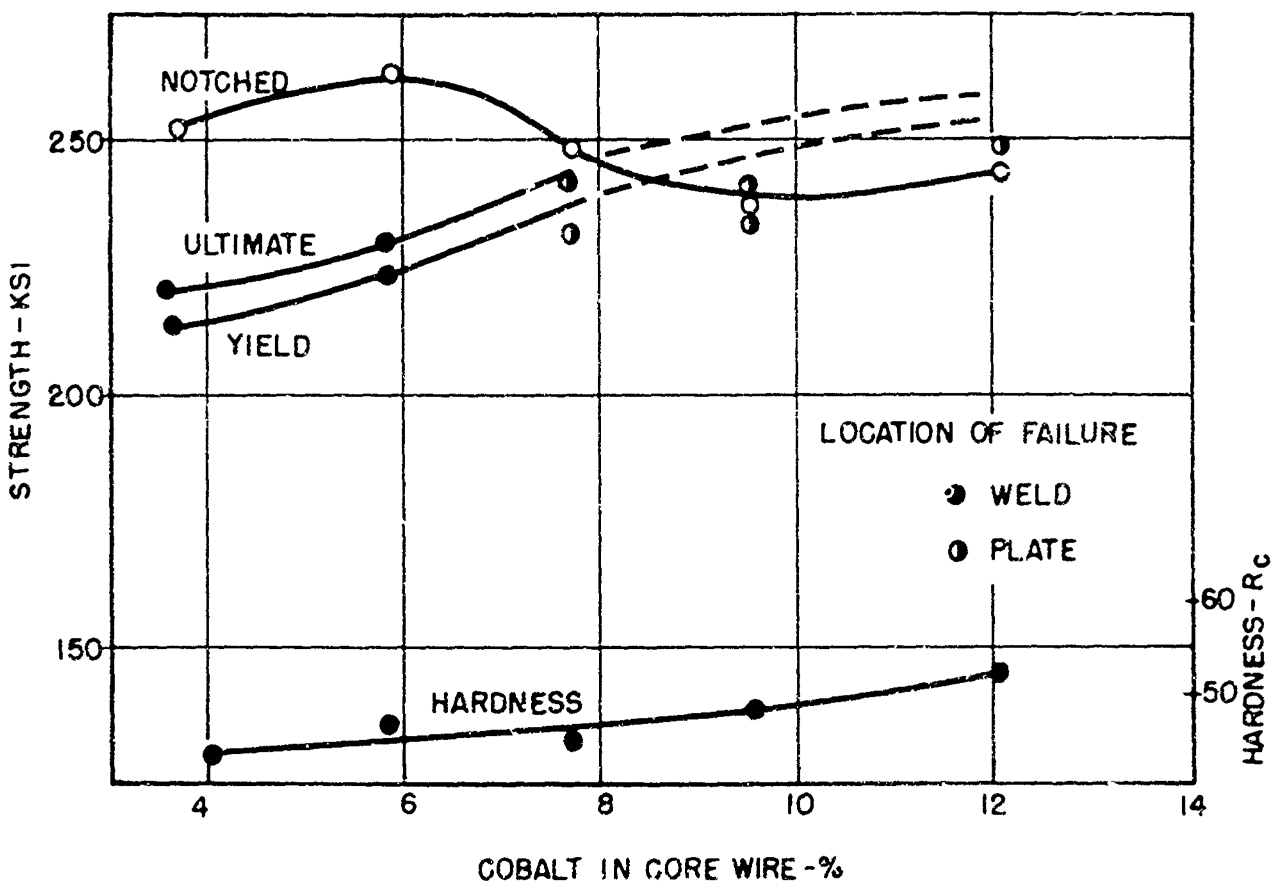


Figure 147

EFFECTS OF HEAT TREATMENT ON YIELD STRENGTH
OF COATED ELECTRODE WELDS (18% NICKEL - 200 KSI)

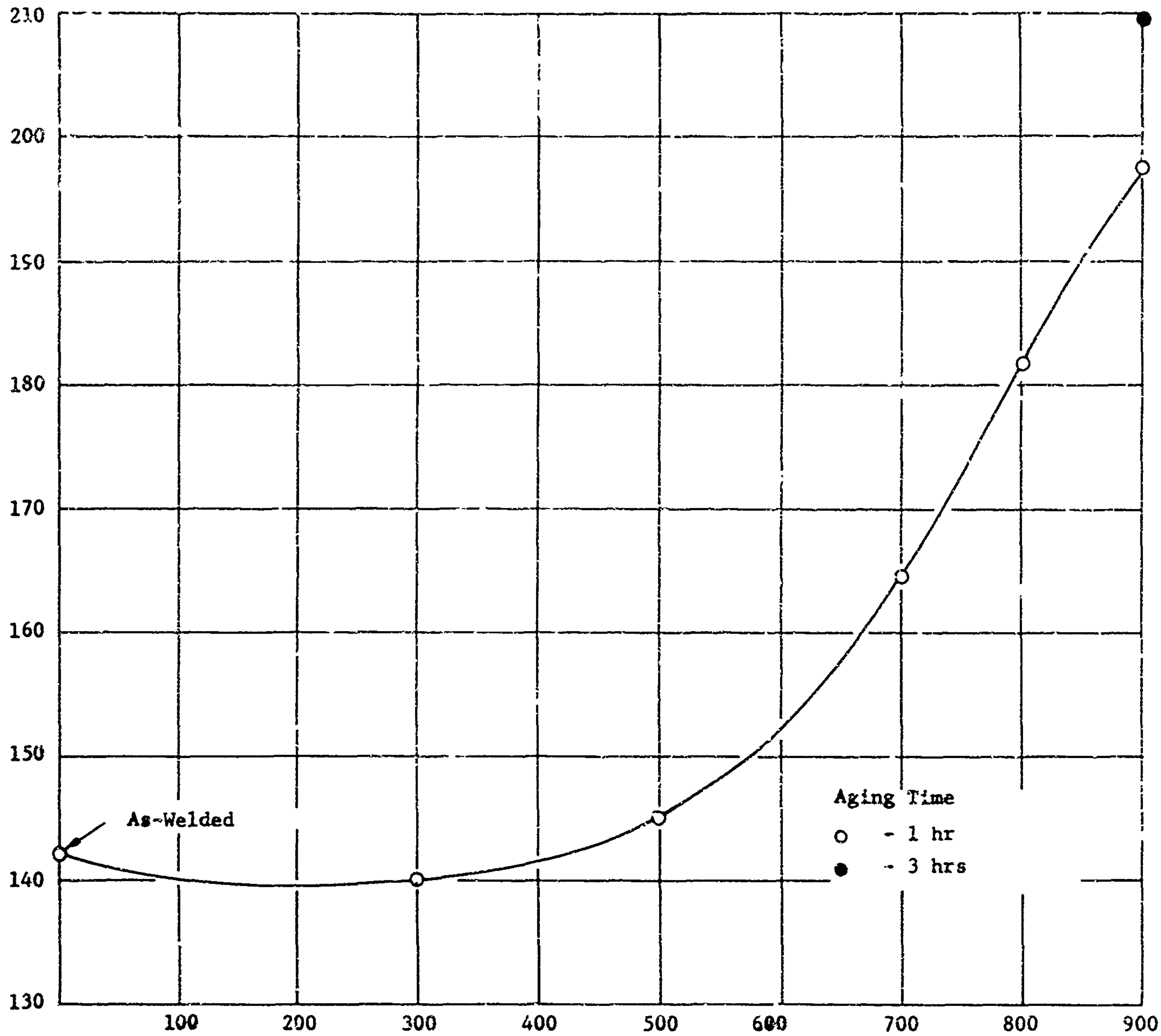
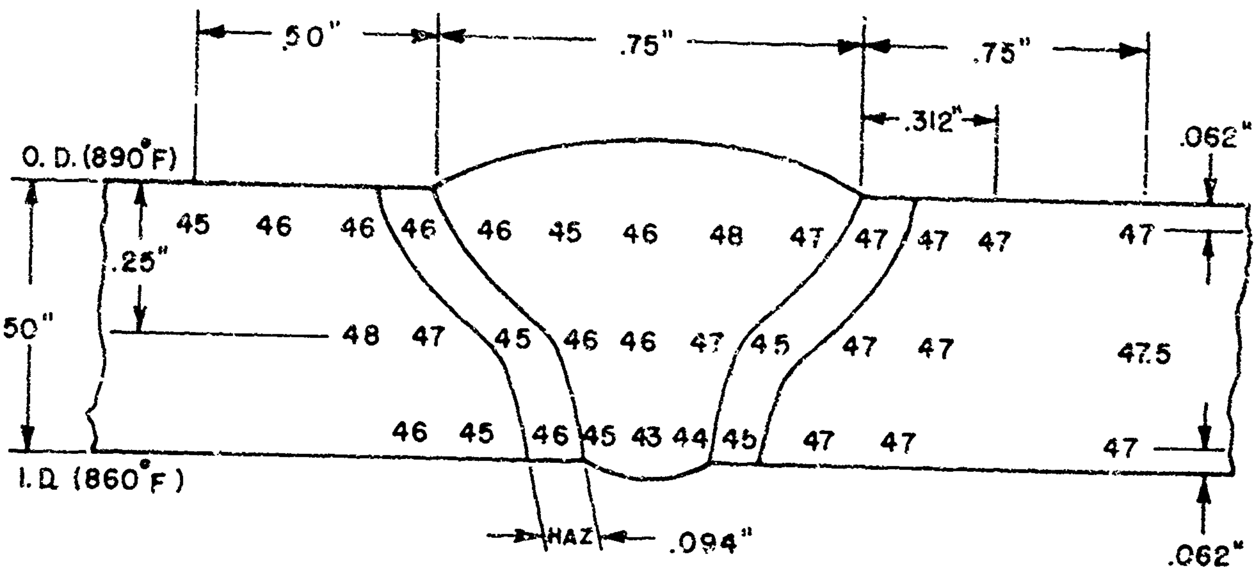


Figure 148

EFFECT OF LOCAL POST WELD INDUCTION HEATING
ON AGING RESPONSE OF 18% Ni STEEL WELD DEPOSIT (250 KSI)

HARDNESS TRAVERSE - Rc (1)



TRANSVERSE CROSS SECTION THROUGH GIRTH WELD

TRANSVERSE WELD JOINT MECHANICAL PROPERTIES (1)

HARDNESS - Rc			TENSILE PROP. (2)				NOTCHED TENSILE PROP. (3)		
WELD	HAZ	BASE METAL	YS KSI	TS KSI	ELONG. %	R.A. %	N.T.S.	NTS/YS	NTS/TS
46	46	47	220	234	8.33	37.2	268	1.21	1.14

(1) Plate: 18 Ni Co Mo - 250 KSI steel (Lo Ti content - 0.24%) aged prior to welding to 235 KSI YS (900°F/3 hrs)

Filler: 18 Ni Co Mo - 250 KSI coated electrode

Heat Treatment: 800°F/1 hr (on heating) + 875°F/1 hr (at temp.)

(2) Round Bar Tensiles: Avg. of 3 tests

(3) Notched Round Bars

Figure 149

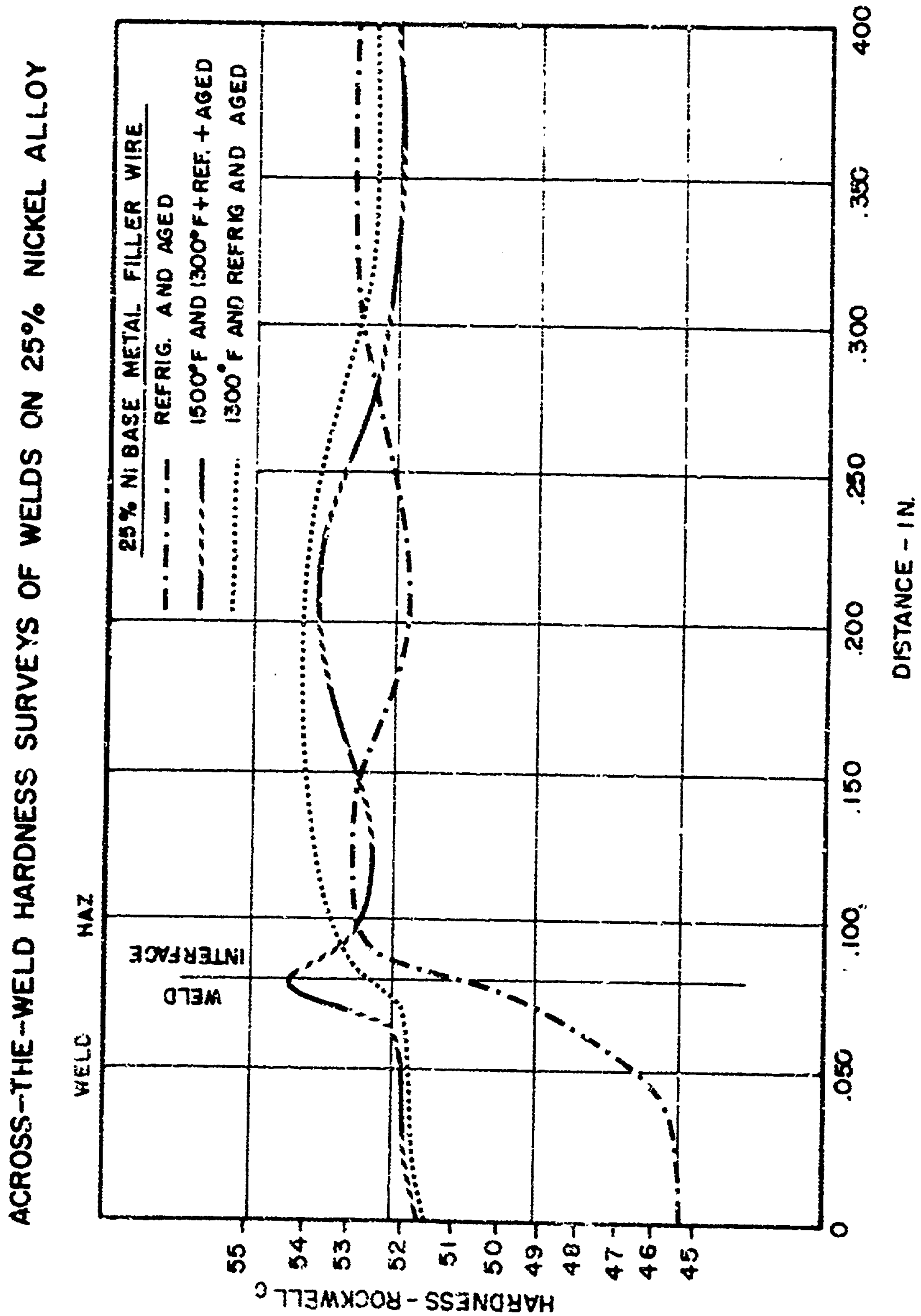
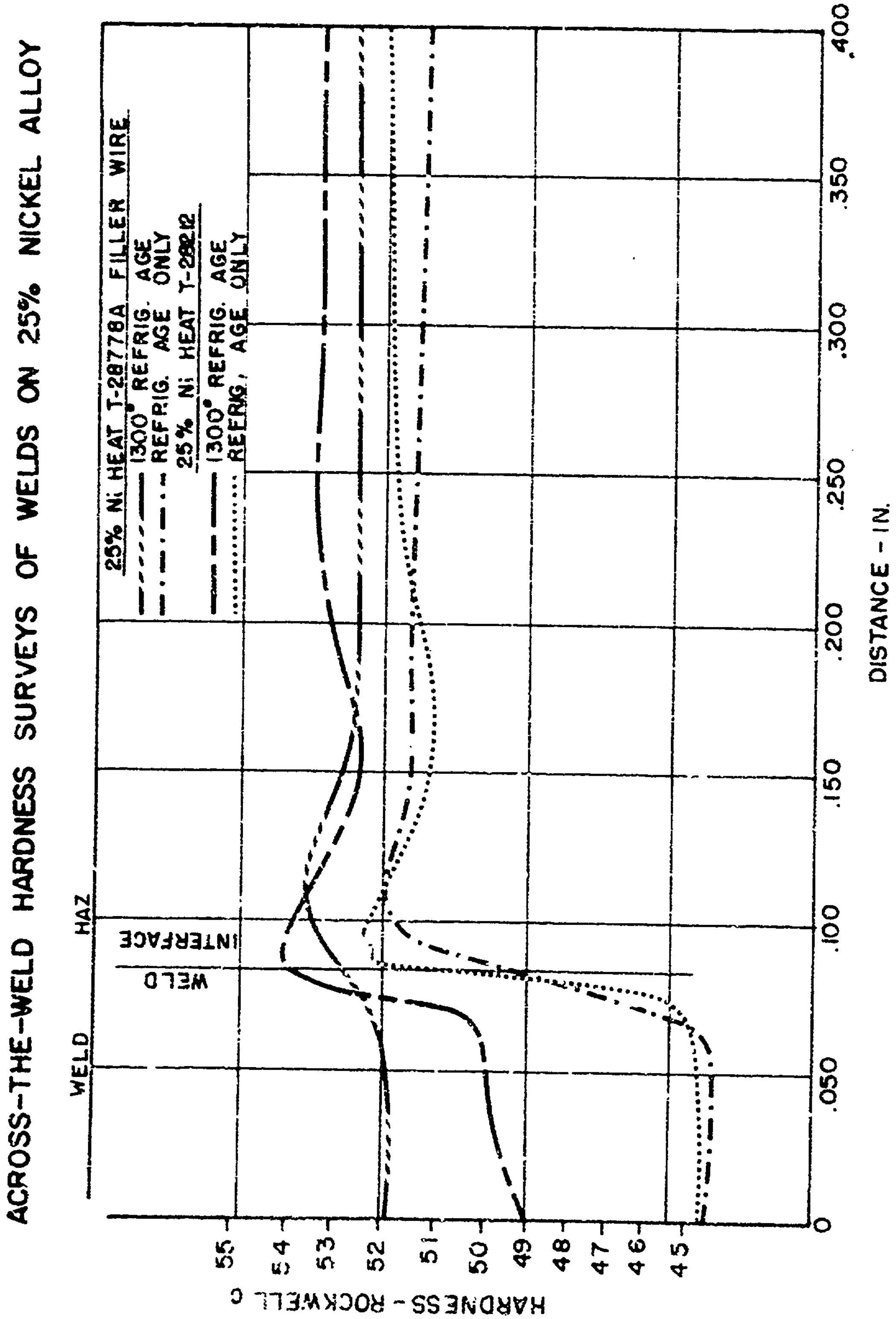

ACROSS-THE-WELD HARDNESS SURVEYS OF WELDS ON 25% NICKEL ALLOY
25% Ni BASE METAL FILLER WIRE
REFRIG. AND AGED
1500°F AND 1300°F + REF. + AGED
1300°F AND REFRIG AND AGED
WELD
HAZ
WELD
INTERFACE
HARDNESS - ROCKWELL C
DISTANCE - IN.

Figure 150



ACROSS-THE-WELD HARDNESS SURVEYS OF WELDS ON 25% NICKEL ALLOY
25% Ni HEAT T-28778A FILLER WIRE
1300° REFRIG. AGE
REFRIG. AGE ONLY
25% Ni HEAT
1300° REFRIG. AGE
REFRIG. AGE ONLY
WELD
HAZ
INTERFACE
WELD
55
54
53
52
51
50
49
48
47
46
45
HARDNESS - ROCKWELL C
0
.050
.100
.150
.200
.250
.300
.350
.400
DISTANCE - IN.

Figure 151

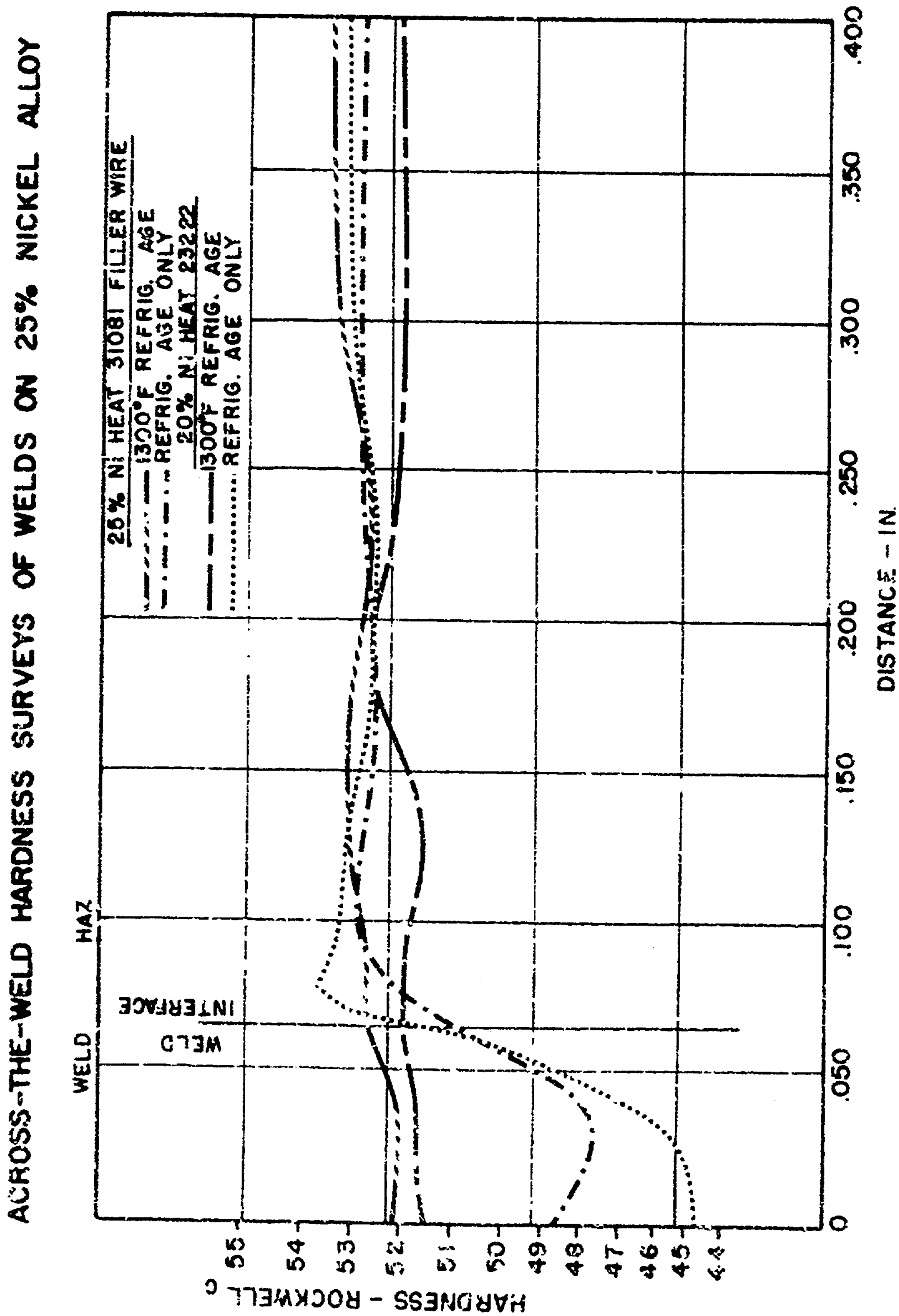

ACROSS-THE-WELD HARDNESS SURVEYS OF WELDS ON 25% NICKEL ALLOY
25% Ni HEAT 31081 FILLER WIRE
1300°F REFRIG. AGE
REFRIG. AGE ONLY
20% Ni HEAT 23222
1300°F REFRIG. AGE
REFRIG. AGE ONLY
WELD
HAZ
WELD
INTERFACE
HARDNESS - ROCKWELL C
55
54
53
52
51
50
49
48
47
46
45
44
DISTANCE - IN
0
.050
.100
.150
.200
.250
.300
.350
.400

Figure 152

TABLE 57

COMPOSITION SPECIFICATION FOR GROUP I ALLOYS

	18% Nickel Alloy (250 KSI Nominal Yield Strength)	18% Nickel Alloy (300 KSI Nominal Yield Strength)
Nickel	18.0 - 19.0%	18.0 - 19.0%
Cobalt	7.0 - 8.0	8.5 - 9.5
Molybdenum	4.6 - 5.1	4.6 - 5.2
Titanium	0.25 - 0.55	0.5 - 0.8
Aluminum	0.10 added	0.10 added
Carbon	0.01 - 0.03	0.01 - 0.03
Silicon	0.10 max.	0.10 max.
Manganese	0.10 max.	0.10 max.
Phosphorous	0.01 max.	0.01 max.
Sulphur	0.01 max.	0.01 max.
Calcium	0.05 added	0.05 added
Boron	0.003 added	0.003 added
Zirconium	0.02 added	0.02 added

TABLE 68

COMPOSITION SPECIFICATIONS FOR GROUP II ALLOYS

	20% Nickel Alloy	25% Nickel Alloy
Nickel	19.0 - 20%	25.0 - 26.0%
Titanium	1.30 - 1.60	1.30 - 1.60
Aluminum	0.15 - 0.30	0.15 - 0.30
Columbium	0.30 - 0.50	0.30 - 0.50
Carbon	0.03 max.	0.03 max.
Silicon	0.10 max.	0.10 max.
Manganese	0.10 max.	0.10 max.
Phosphorus	0.10 max.	0.01 max.
Sulphur	0.01 max.	0.01 max.
Calcium	0.05 added	0.05 added
Boron	0.003 added	0.003 added
Zirconium	0.02 added	0.02 added

It is suggested that the above composition specifications should be rigidly followed until enough statistical data is accumulated from production heats to warrant appropriate changes.

TABLE 69

CORROSION RESISTANCE OF THE 18 Ni - 7.5 Co - 5 Mo IRON ALLOYS IN ARTIFICIAL SEA WATER
(INCO DATA)

Ni	Co	Mo	Ti	Marage °F	Marage Hr	Marage °F	Marage Hr	Yield Strength PSI	U-Bend Days	3-Point Load Days*
18.3	7.0	4.8	.4	1500	1	900	1	232,000	Unbroken, 120	
						900	1	232,000	Broke, 92-99	
						900	1	232,000	Unbroken, 140	
						900	3	246,000		Unbroken, 140
						900	3	246,000		Unbroken, 140
18.2	6.8	4.9	.4	1500	1	900	3	237,000	Broke, 35-45	
18.4	7.0	5.1	.4	1500	1	900	3	266,000	Broke, 35-45	
18.4	7.0	5.1	.4	1500	1	900	3	272,000	Unbroken, 82	
18.1	7.2	5.0	.4	1500	1	900	3	249,000	Broke, 35-45	
18.3	6.8	5.2	.4	1500	1	900	3	246,000	Unbroken, 82	
18.4	7.6	5.2	.4	1500	1	900	3	248,000	Broke, 35-45	

* Stress = Yield Strength

Table 70

EFFECT OF ALLOY COMPOSITION ON WELD CRACKING (1)

Electrode Core Wire Variable (2) (Per Cent)			Weld Metal Recovery (Per Cent)			Weld Metal Hardness (Rc)			Weld Cracking (Cracks Per
Ti	Al	Mn	Ti	Al	Mn	As-Welded	After 900°F, 3 Hr. Marage	Weld Porosity	X-Weld Section)
<.1	-	-	<.1	-	-	30.	36.	Gross	>40.
.49	-	-	<.1	-	-	30.	35.	Slight	>40.
1.00	-	-	.17	-	-	31.	38.	None	>40.
1.39	-	-	.19	-	-	36.	41.	None	21.4
1.84	-	-	.22	-	-	32.	40.	None	4.0
2.96	-	-	.81	-	-	33.	47.	None	0.0
-	<.03	-	-	<.1	-	30.	41.	Gross	>40.
-	.50	-	-	<.1	-	29.	42.	None	>40.
-	.99	-	-	.14	-	33.	42.	None	>40.
-	1.55	-	-	.24	-	36.	47.	None	8.5
-	2.15	-	-	.43	-	32.	47.	None	8.0
-	3.43	-	-	.80	-	37.	50.	None	0.0
-	-	.095	-	-	<.005	26.	40.	None	>40.
-	-	1.02	-	-	.49	32.	37.	None	29.0
-	-	2.05	-	-	1.07	27.	35.	None	1.0
-	-	3.00	-	-	1.73	24.	35.	None	2.5
-	-	4.05	-	-	2.15	14.	17.	None	3.0
-	-	5.00	-	-	3.05	4.	2.	None	2.0

(1) All coated-electrode welds on aged Ni-Co-Mo steel (46 Rc) having the following composition (%):

Fe	Ni	Co	Mo	Ti	C
Bal.	18.5	6.5	7.5	.3	.[illegible]

(2) In a base composition (%) of:

Fe	Ni	Co	Mo	Ti	C	Al	Mn	Si
Bal.	18.5	3.5	5.	.4	.05	.2	.1	.1

TABLE 71

SHEET WELD TENSILE AND FRACTURE TOUGHNESS PROPERTIES (1)(2)
18% NICKEL ALLOY (250 KSI)

Condition (3)	0.2% Y.S. KSI	UTS KSI	Elong. %	RT %	Net Fracture Stress KSI	Notched Strength KSI	Kc KSI in.	Gc in-lb/in^2		Crit. Crack Length in.
As-Welded	131	154	3.5	30	195	167	-	-		
Ref (-110°F/16 hrs.)	132	155	4.0	29	201	171	-	-	-	-
900°F/3 hrs.	227	230	2.0	26	246	215	>178	>1150	> 9.7	>0.19
950°F/3 hrs.	219	224	2.5	22	242	185	-	-	-	-
1500°F/1 hr. + 900°F/3 hrs.	219	226	2.5	15	237	207	-	-	-	-

(1) Filler wire composition: 16 Ni, 8 Co, 4.5 Mo, .4 Ti

(2) .06-.08" thick sheet, NASA - 1" edge notched specimen, .0005" root radius, $K_t > 20$

(3) Single test specimens per condition

TABLE 72

TRANSVERSE WELD TENSILE PROPERTIES
IN 18% Ni STEEL PLATE (250 KSI) (1) (2)

(Aged: 900°F/3 hrs.)

Welding Process	Y.S. (KSI)	T.S. (KSI)	Elong. (%)	RA (%)	NTS	NTS:UTS Ratio
Gas, Metal-Arc (MIG)	232	240	5	35	281	1.17
Coated Electrode (3)	226	235	5	20	276	1.17
Submerged (3) Arc	226	233	9	47	232	1.0

(1) Heat low in Ti content (0.24% Ti)

(2) Filler materials - 250 KSI compositions

(3) Failure in plate

Table 73

Composition Specification For Group I Filler Wires

(18% Nickel Alloy)

ELEMENT	WEIGHT - PERCENT	
	250 KSI	300 KSI
Nickel	17.5 - 18.5	17.5 - 18.5
Cobalt	7.5 - 8.5	8.5 - 9.5
Molybdenum	4.0 - 5.0	4.0 - 5.0
Titanium	0.35- 0.50	0.5 - 0.8
Aluminum	0.1 Added	0.1 Added
Carbon	0.03 max.	0.03 max.
Silicon	0.1 max.	0.1 max.
Manganese	0.1 max.	0.1 max.
Phosphorus	0.01 max.	0.01 max.
Sulfer	0.01 max.	0.01 max.
Calcium	None Added	None Added
Boron	None Added	None Added
Zirconium	None Added	None Added
Iron	Balance	Balance

TABLE 74

SHEET WELD TENSILE AND FRACTURE TOUGHNESS PROPERTIES (1)(2) (20% AND 25% NICKEL ALLOYS)

Alloy	Condition	0.2% Y.S. KSI	U.T.S. KSI	Elong. %	R.T. %	Net Fracture Stress KSI	Notched Strength KSI	Kc KSI $\sqrt{in.}$	Gc in-lb/in^2	β	Critical Crack Length in.
20% Ni	As-Welded	126	137	2	12.3	-	-	-	-	-	-
	850°F/1-2 hrs (3)	210-217	214-223	2.0	20	204-240	180-203	112- >150	500- >900	4.6- >8.2	.089- > .160
25% Ni	As-Welded	104	157	7.5	22	196	148	>144	>785	>41.6	>.612
	1300°F/1 hr. + Ref. -110°F/16 hrs. + 850°F/2 hrs. (4)	217-220	228-232	2.0	24-33	193-203	176-178	122-129	557-630	6.7-6.9	.098-.111

(1) Filler Wire Compositions

20% Ni - 20 Ni, 1.7 Ti, .22 Al, 1.6 Mo
25% Ni - 25 Ni, 1.7 Ti, .3 Al, 1.6 Mo

(2) .06-.08" Thick Sheet, NASA-1" Edge Notched Specimen, .0005" Root Radius, Kt>20

(3) Four Test Specimens

(4) Two Test Specimens

TABLE 75

Composition Specification For Group II Filler Wires

(20 and 25% Nickel Alloys)

	WEIGHT PERCENT	
ELEMENT	20% NICKEL ALLOY	25% NICKEL ALLOY
Nickel	19 - 20	25 - 26
Titanium	1.6-1.8	1.6-1.8
Aluminum	0.15-0.30	0.15-0.30
Columbium	None Added	None Added
Molybdenum	1.40-1.60	1.40-1.60
Carbon	0.03 max.	0.03 max.
Silicon	0.10 max.	0.10 max.
Manganese	0.10 max.	0.10 max.
Phosphorus	0.10 max.	0.01 max.
Sulfer	0.01 max.	0.01 max.
Calcium	None Added	None Added
Boron	None Added	None Added
Zirconium	None Added	None Added
Iron	Balance	Balance

1.3 Comparison Between Properties of Laboratory and Production Heats

One of the most important questions which arises during the course of new alloy development is whether or not large heats will yield properties equivalent to the small laboratory development heats. Before a new alloy makes the transition to a recognized engineering material, several important, practical questions should be answered, such as:

a. The relative effect of the various melting methods on the mechanical and toughness properties of the material.

b. The effect of heat size on properties.

c. The effect of the extremes in chemical composition limits on properties.

d. The relative effect of the various elements in production heats on properties.

e. The effect of section size on properties.

f. The effect of mill processing variables on properties.

This section of the report presents a comparison of properties between the development heats and available production heats.

1.3.1 18% Nickel Alloy (250 KSI)

The properties of nine (9) production heats of the 18% nickel alloy (250 KSI) were collated and evaluated. The producers, compositions, heat sizes and melting methods are reported in Tables 76 and 77. Yield strengths and notched bar ultimate versus smooth bar ultimate ratios are reported as a function of titanium content in Figure 76. Inspection of Figure 76 indicates that the production heats produced higher yield strengths and notched-to-smooth ratios than laboratory heats at comparable titanium levels.

Consequently it is deduced that no difficulty should be experienced in achieving anticipated strength and toughness in production heats.

1.3.2 18% Nickel Alloy (300 KSI)

Properties of eight (8) production heats of the 18% Nickel alloy (300 KSI) were available for comparison. However, five (5) heats were out of the recommended composition range and consequently, are not reported.

The three remaining heats which were within the recommended chemistry are reported in Table 78. These heats meet the expected strength and toughness when compared to the laboratory heat data reported in Table 79. No difficulties in achieving the desired properties with production size heats is anticipated based upon these results.

1.3.3 20% Nickel Alloy

The available data on seven (7) production size heats of the 20% nickel alloy, ranging in size from 1000 to 28,000 pounds, were compared with the laboratory development heats. The producers, compositions, melting methods and heat sizes are tabulated in Tables 80 and 81. Mechanical properties of bar stock fabricated from these heats are reported in Tables 82, 83, and 84. A comparison of properties with the laboratory heats is shown in Figure 77.

All production heats exhibited comparable strength. Heat K51888 exhibited low ductility. The low ductility was attributed to the presence of sulphide forms. This problem has been subsequently overcome by the addition of calcium to the heats. In general, the properties of production heats are above those of the laboratory heats at low titanium contents. The production heat properties approach laboratory heat properties at higher titanium contents. The above comparison shows that adequate strength in commercial size heats can readily be achieved by proper composition and process control.

1.3.4 25% Nickel Alloy

The representative properties of seven large heats of the 25% nickel alloy have been accumulated. Of the seven heats, four were melted by the Allegheny Ludlum Steel Corporation and the remaining three by Special Metals, Incorporated. The chemical compositions of these heats are presented in Table 85. Tensile properties as a function of heat treatment are presented in Tables 86 and 87.

A graphic presentation comparing the properties of large heats against small laboratory heats is made in Figure 155. It is evident that all large heats, with the exception of Heat No. 23315, more than matched the properties of the laboratory heats. Heat No. 23315 contained high nickel and titanium contents, drastically lowering the M_s temperature. As a result, large amounts of retained austenite were present, thereby lowering the strength values substantially below those reported for the other large heats.

COMPARISON OF LARGE HEAT PROPERTIES WITH LABORATORY HEAT RESULTS – 250 KSI NOMINAL YIELD STRENGTH 18% NICKEL ALLOY

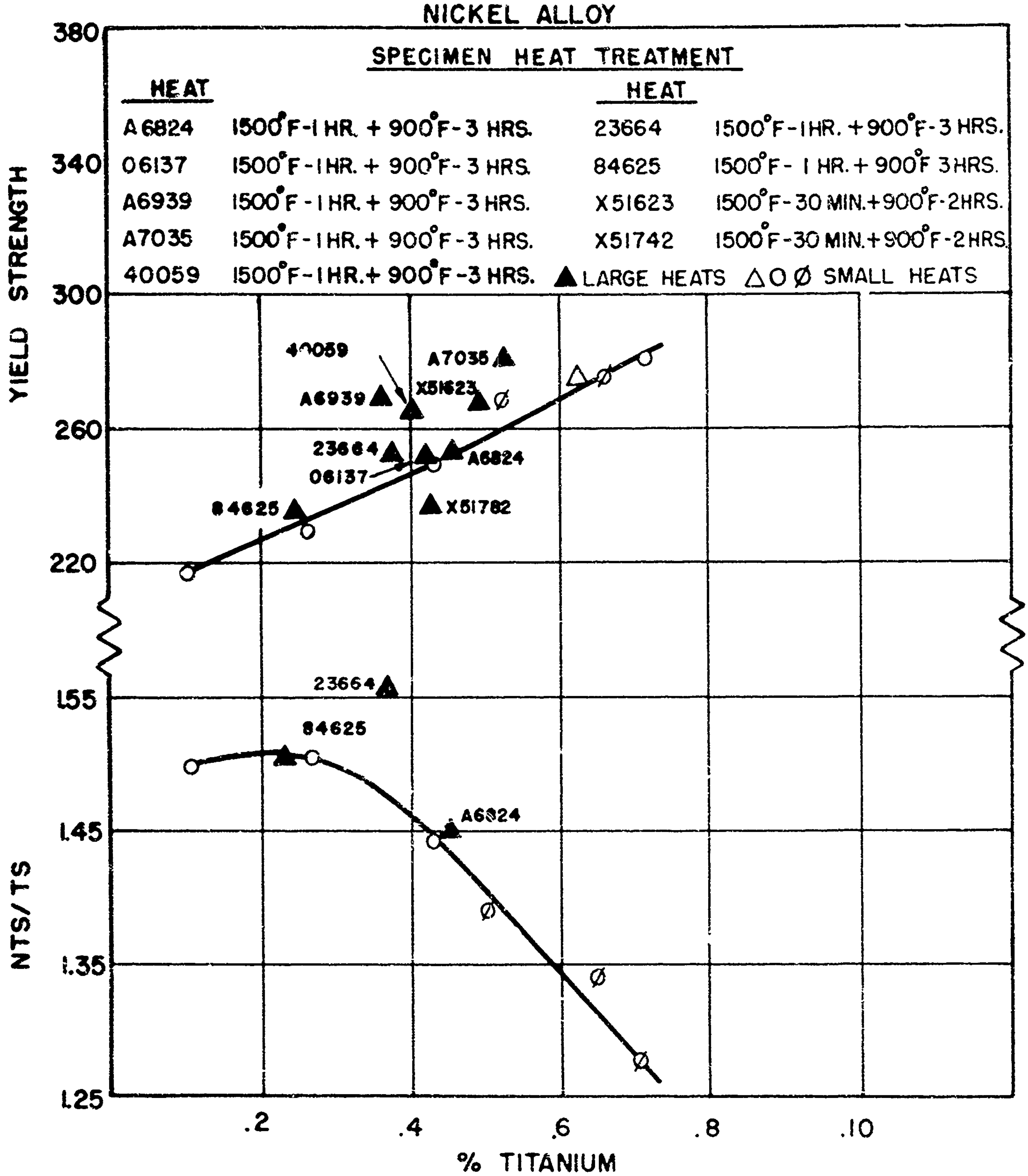


Figure 153

5332

COMPARISON OF LARGE HEAT PROPERTIES WITH LABORATORY HEAT RESULTS - 20% NICKEL ALLOY

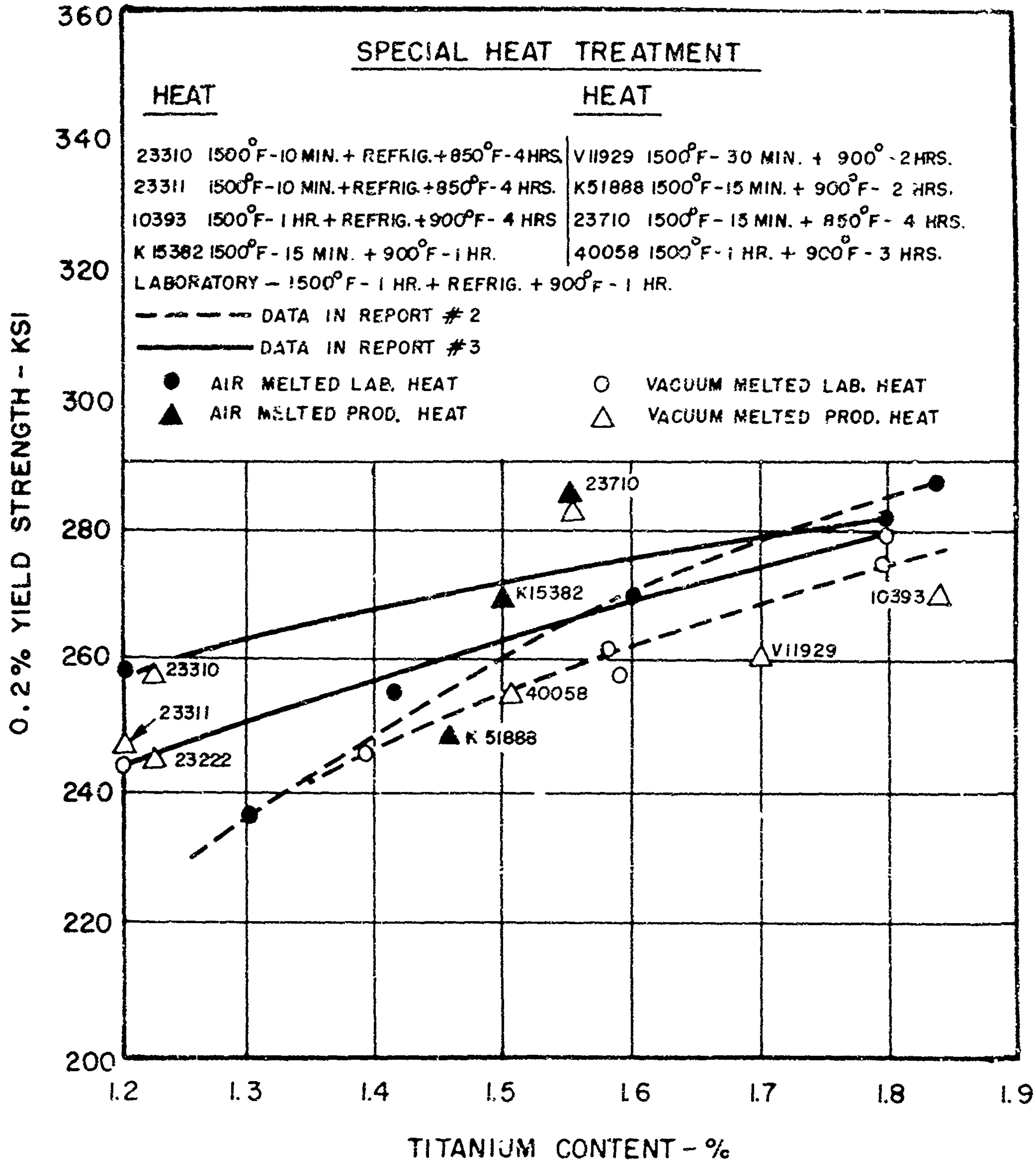


Figure 154

COMPARISON OF LARGE HEAT PROPERTIES WITH LABORATORY HEAT RESULTS - 25% NICKEL ALLOY

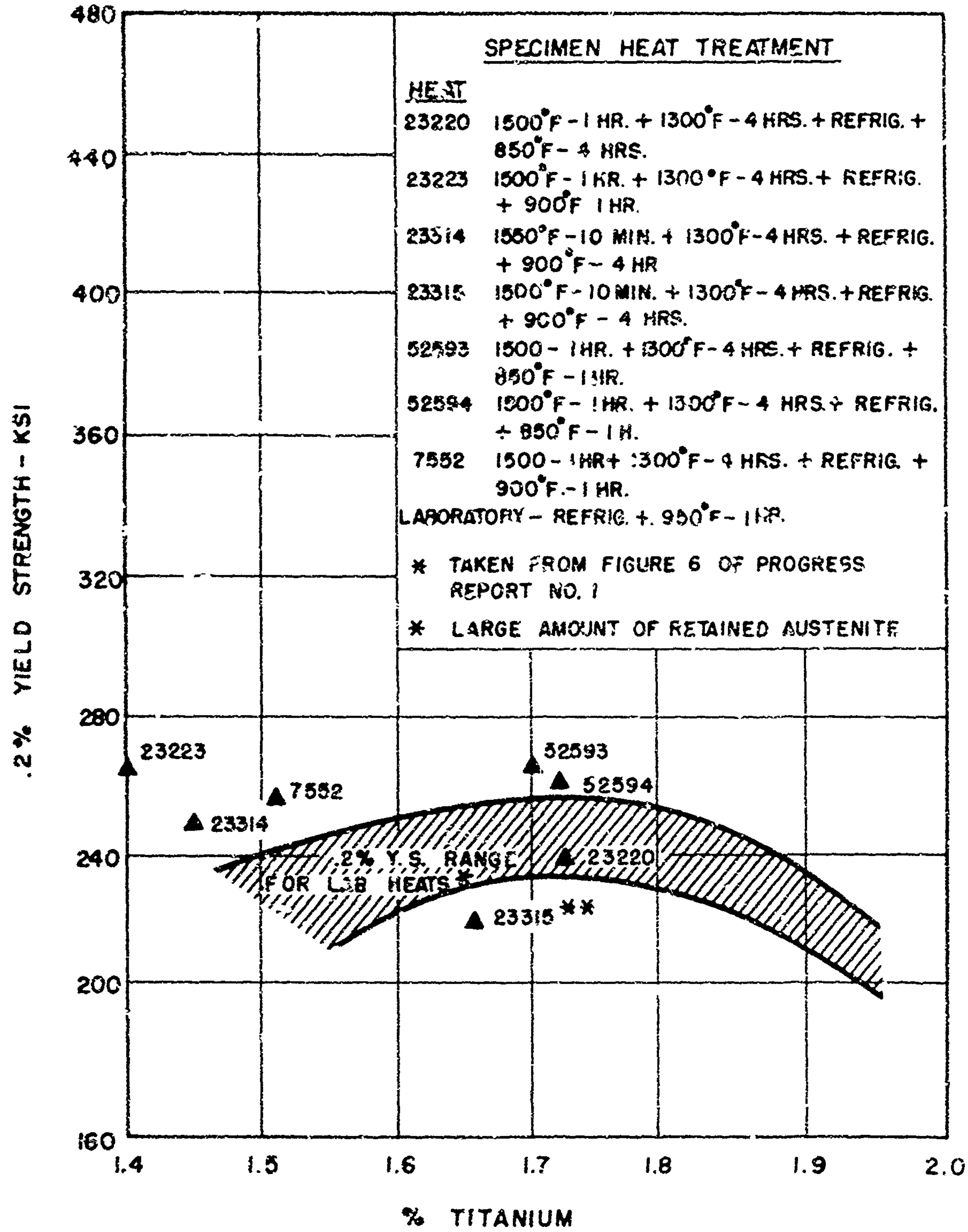


Figure 155

5322

TABLE 76

COMPOSITION OF RECENT PRODUCTION 250 KSI NOMINAL YIELD STRENGTH 18% NICKEL ALLOY HEATS

Producer	Heat #	Size of Heat	Melting Practice	C	Mn	P	S	Si	Ni	Ti	Al	Mo	Co	B	Zr	Ca
Carpenter Steel	X-51623	28000	Air Arc	0.026	0.05	0.003	0.010	0.09	18.34	0.47	0.15	4.62	7.61	-	-	-
Carpenter Steel	X-51742	28000	Air Arc	0.022	0.02	0.003	0.008	0.10	17.63	0.42	0.079	4.80	7.32	-	-	-
Carpenter Steel	X-51860	28000	Air Arc-Consumable Electrode Remelt	0.029	0.06	0.0006	0.009	0.09	17.63	0.50	0.08	4.77	7.26	0.0038	-	0.01
Vanadium Alloy Steel	A6824	1000	Air Induction	0.02	0.11	0.007	0.007	0.09	18.54	0.44	0.095	5.34	7.38	0.003*	0.01*	0.06*
Vanadium Alloy Steel	06137	1000	Air Induction Consumable Electrode Remelt	0.01	0.11	0.007	.004	0.07	18.2	0.42	0.09	4.8	7.6	0.004	-	0.05*
Vanadium Alloy Steel	A6939	1000	Air Induction	0.03	0.15	0.004	0.013	0.09	18.2	0.35	.005	4.7	7.4	0.002	-	0.05*
Vana[illegible] Alloy [illegible]teel	A7035	1000	Air Induction	0.02	0.10	0.004	0.011	0.07	18.7	0.50	.11	4.8	7.5	0.003*	0.01*	0.05*
Latrobe Steel	40059	4000	Air Arc-Consumable Electrode Remelt	0.03	0.03	0.003	0.006	0.0351	19.1	0.40	.04	4.4	8.2	0.003	0.02	0.05*
Allegheny-Ludlum Steel	23664	1000	Air Induction Consumable Electrode Remelt	0.016	0.05	0.002	0.007	0.06	18.2	0.37	0.09	4.8	8.0	0.004	0.01	0.05*

TABLE 77

PROPERTIES OF RECENT PRODUCTION 250 KSI NOMINAL YIELD 18% NICKEL ALLOY HEATS

Heat No	Size of Heat (lbs)	Melting Method	Heat Treatment	Data Source	Specimen Form	U.T.S. KSI	0.2% Y.S. KSI	% Elong. in 4D	% R.A.	Notch Tensile KSI	N.T.S. (Sheet) KSI	N.F.S. KSI	K_c	G_c
X-51623	28000	Air Arc	1500°F-30 min +950°F- 2 hrs	Carpenter Steel	Bar, Transverse from 9" RCS	272.4 269.5 269.0 269.0 274.5 271.9	268.9 265.5 264.5 265.5 - 270.9	9.2 7.0 6.8 6.8 7.6 6.8	44.8 34.7 29.2 37.0 39.6 27.7					
X-51742	28000	Air Arc	1500°F-30 min +900°F- 2 hrs	Carpenter Steel	Bar, Transverse from 9" RCS	240.0 252.1	231.6 243.0	10.0 7.4	43.7 31.6					
X-51660	28000	Air Arc-Consumable Electrode Remelt	1500°F-30 min +950°F- 2 hrs	Carpenter Steel	Bar	274.3 272.8 269.1 270.0	- 264.3 - 262.0	9.0 7.3 6.8 9.7	40.8 40.3 33.1 41.9					
A6824	1000	Air Induction-Consumable Electrode Remelt	1500°F- 1 hr +900°F- 3 hrs	Vanadium Alloy Steel	Bar from 5/8" bar	264.6 266.1 263.8 263.3	256.8 258.9 252.5 254.8	11.5 11.5 12.0 12.0	59.8 58.3 57.0 58.4	365				
06137	1000	Air Induction-Consumable Electrode Remelt	1500°F- 1 hr +900°F- 3 hrs	Vanadium Alloy Steel	Bar from 1-1/2" RCS	264 263 264	257 254 253	10 11 13	62 63 61					
A6939	1000	Air Induction	1500°F 1 hr +900°F- 3 hrs	Vanadium Alloy Steel	0.195 Sheet Transverse	268 265 272 283	261 258 267 276	5 4 5 4	35 37 47 45					
A7335	1000	Air Induction	1500°F- 1 hr +900°F- 3 hrs	Vanadium Alloy Steel	0.195 Sheet Transverse	280 278 282 279 280 286	276 266 280 274 277 282	6 6 6 6 6 6	40 40 39 38 35 37					
43059	4000	Air Arc-Consumable Electrode Remelt	1500°F- 1 hr +900°F- 3 hrs	Vanadium Alloy Steel	Bar, Transverse from 10" RCS	271.1 268.5 271.5	265.2 261.5 263.3	9 10 10	42 45 44					
23664	1000	Air Induction	1500°F-30 min +900°F- 3 hrs	Inco	0.067" Sheet	279	274	3	-	-	255	288	182	1220
			1500°F- 1 hr + 50% CW +900°F- 3 hrs		0.050 Sheet	312	310	2	-	-	253	295	191	1343, 1457
			1500°F- 1 hr +900°F- 3 hrs		Bar	268	257	12	57	401				
			900°F- 3 hrs		Bar					416				

TABLE 78

COMPOSITION OF RECENT PRODUCTION 300 KSI
NOMINAL YIELD STRENGTH 18% NICKEL ALLOY HEATS

Producer	Heat No.	Size of Heat	Melting Practice	C	Mn	P	S	Si	Ni	Ti	Al	Mo	Co	B	Zr	Ca
Latrobe Steel	06269	1000	Vacuum Melt Remelt	0.008	0.10	0.006	0.013	0.10	18.3	0.65	0.03	4.8	9.0	0.002	0.01	0.05*
Standard Steel	E-3637	30000	Vacuum Melt Remelt	0.025	0.05	0.017	0.004	0.10	18.87	0.57	0.09	4.88	9.02			
Latrobe Steel	C-40148	20000	Vacuum Melt Remelt	0.026	0.04	0.003	0.009	0.06	19.08	0.60	0.11	4.80	8.59			

* Added

PROPERTIES OF RECENT PRODUCTION 300 KSI
NOMINAL YIELD STRENGTH 18% NICKEL ALLOY HEATS

Heat No.	Size of Heat (lbs)	Melting Method	Heat Treatment	Data Source	Specimen Form	U.T.S. KSI	0.2% Y.S. KSI	% Elong. in 4D	% R.A.	N.T.S. KSI
06269	1000	Vacuum Melt Remelt	1500°F - 1 hr. + 900°F - 3 hrs.	Latrobe	0.195" Sheet	312	310	6	31	
						315	310	5	33	
						314	307	5	31	
E-3637	30000	Vacuum Melt Remelt	1500°F - 1 hr. + 850°F - 3 hrs.	Standard Steel	Bar	273.6	261.6	11.0	47.1	374.7
						272.0	259.6	10.5	46.5	368.3
			1500°F - 1 hr. + 875°F - 3 hrs.			278.6	264.5	9.5	47.1	361.9
						271.6	258.4	9.5	42.3	375.4
			1500°F - 1 hr. + 900°F - 3 hrs.			284.0	274.7	10.0	45.5	380.4
						281.0	272.1	5.0	20.2	372.0
			1500°F - 1 hr. + 925°F - 3 hrs.			286.7	274.4	11.0	47.9	374.8
						284.6	276.6	7.0	45.3	345.4
			1500°F - 1 hr. + 950°F - 3 hrs.			288.9	280.7	9.5	45.3	334.6
						287.3	279.7	10.0	46.5	378.0
C-40148	20000	Vacuum Melt Remelt	1500°F - 1 hr. + 900°F - 3 hrs.	Latrobe	Bar	293.4	283.4	10	44	
						290.3	277.3	10	42	
						281.3	268.4	9	37	
						283.6	270.5	9	37	

Table 79

COMPOSITION OF LABORATORY AND PRODUCTION 300 KSI NOMINAL YIELD STRENGTH 18% NICKEL ALLOY HEATS

Producer	Heat Number	Size of Heat	Melting Method	C	Mn	P	S	Si	Ni	Ti	Al*	Mo	Co	B**	Zr***
Allegheny Ludlum	-	35	Vac. Melt Consutrode Remelt	.01/.03	0.1 max	.01 max	.01 max	0.1 max	17/19	.40	0.1	3/3.5	8/9	.003	.02
Allegheny Ludlum	-	35	Vac. Melt Consutrode Remelt	.01/.03	0.1 max	.01 max	. 1 max	0.1 max	17/19	.55	0.1	3/3.5	8/9	.003	.02
Allegheny Ludlum	-	35	Vac. Melt Consutrode Remelt	.01/.03	0.1 max	.01 max	.01 max	0.1 max	17/19	.71	0.1	3/3.5	8/9	.003	.02
Allegheny Ludlum	-	35	Vac. Melt Consutrode Remelt	.01/.03	0.1 max	.01 max	.01 max	0.1 max	17/19	.73	0.1	3/3.5	8/9	.003	.02
Allegheny Ludlum	-	35	Vac. Melt Consutrode Remelt	.01/.03	0.1 max	.01 max	.01 max	0.1 max	17/19	.84	0.1	3/3.5	8/9	.003	02
Allegheny Ludlum	-	35	Vac. Melt Consutrode Remelt	.01/.03	.01 max	.01 max	.01 max	0.1 max	17/19	1.0	0.1	3/3.5	8/9	.003	.02

TENSILE PROPERTIES OF LABORATORY AND PRODUCTION 300 KSI NOMINAL YIELD STRENGTH 18% NICKEL ALLOY HEATS

Heat Number	Size of Heat (lbs.)	Melting Method	Heat Treatment	Data Source	Spec. Form	U.T.S. KSI	.2% Y.S. KSI	Elongation %	R.A. %	NTS/TS Ratio
Allegheny	35	Vac. Melt Consutrode Remelt	1500°F/1 hr + 900°F/3 hrs.	Allegheny	Sheet	274.0	268.0	5.9	46.6	0.95
Allegheny	35	Vac. Melt Consutrode Remelt	1500°F/1 hr. + 900°F/3 hrs.	Allegheny	Sheet	283.0	277.0	5.2	45.3	0.85
Allegheny	35	Vac. Melt Consutrode Remelt	1500°F/1 hr. + 900°F/3 hrs.	Allegheny	Sheet	297.0	294.0	5.0	41.3	0.75
Allegheny	35	Vac. Melt Consutrode Remelt	1500°F/1 hr. + 900°F/3 hrs.	Allegheny	Sheet	308.0	304.0	4.9	43.1	-
Allegheny	35	Vac. Melt Consutrode Remelt	1500°F/1 hr. + 900°F/3 hrs.	Allegheny	Sheet	310.0	308.0	4.6	39.0	0.67
Allegheny	35	Vac. Melt Consutrode Remelt	1500°F/1 hr. + 900°F/3 hrs.	Allegheny	Sheet	324.0	322.0	4.4	38.7	0.53

TABLE 80

COMPOSITION OF PRODUCTION 20% NICKEL ALLOY HEATS

PRODUCER	HEAT#	SIZE OF HEAT	MELTING METHOD	C	Mn	P	S	Si	Ni	Ti	Al	Cb	B	Zr	Ca	Fe
1) Allegheny-Ludlum Steel Corp.	23310	5000	Air induction, Consutrode Remelt	0.007	0.17	0.006	0.003	0.02	19.88	1.24	0.26	0.47	N.A.	N.A.	N.A.	Bal.
2) Allegheny-Ludlum Steel Corp.	23311	5000	Air induction Consutrode, Remelt	0.008	0.15	0.001	0.005	0.03	19.96	1.20	0.26	0.49	N.A.	N.A.	N.A.	Bal.
3) Allegheny-Ludlum Steel Corp.	23221	5000	Air induction, Consutrode Remelt	0.008	0.11	0.008	0.003	0.12	20.42	1.73	0.042	0.43	N.A.	N.A.	N.A.	Bal.
4) Allegheny-Ludlum Steel Corp.	23222	5000	Air induction, Consutrode Remelt	0.007	0.11	0.007	0.002	0.15	20.04	1.27	0.22	0.52	N.A.	N.A.	N.A.	Bal
5) Carpenter Steel Co.	K15382	2000	Air induction, Consutrode Remelt	0.006	0.01	0.005	0.004	0.06	19.81	1.48	0.22	0.32	.0029	N.A.	N.A.	Bal
6) Allegheny-Ludlum Steel Corp.	10393	1000	Air induction, Consutrode Remelt	0.013	0.075	0.002	0.005	0.11	20.07	1.94	0.46	0.51	0.002	0.004	N.A.	Bal
7) Carpenter Steel Co.	V11929	1500	Vacuum Induction	0 009	0.01	0.005	0.004	0.09	20.29	1.70	0.23	0.44	0.0031	N.A.	N.A.	Bal.

TABLE 81

COMPOSITION OF RECENT PRODUCTION 20% NICKEL ALLOY HEATS

Producer	Heat #	Size of Heat	Melting Practice	C	Mn	P	S	Si	Ni	Ti	Al	Cb	B	Zr	Ca
Carpenter Steel	K-51888	28000	Air Arc - Consumable Electrode Remelt	0.029	0.09	0.008	0.010	0.12	20.05	1.46	0.27	0.19	0.0030	0.01	-
Allegheny Ludlum Steel	23710	1000	Air Induction -Consumable Electrode Remelt	0.011	0.054	0.003	0.004	0.057	20.11	1.55	0.27	0.50	0.006	0.01	0.05*
Latrobe Steel	40058	4000	Air Arc -Consumable Electrode Remelt	0.029	0.07	0.004	0.010	0.08	21.2	1.51	0.33	0.48	0.005	0.015	0.05*

TABLE 82

TENSILE PROPERTIES OF LARGE 20% NICKEL HEATS MELTED BY THE ALLEGHENY LUDLUM STEEL CORPORATION

Heat No.	Size of Heat (lbs)	Melting Method	Heat Treatment	Data Source	Specimen Form	Direction	% Cold Reduct.	UTS KSI	.2% YS KSI	Elong. %	R.A. %
23310	5000	Air induction Consutrode Remelt	CW + 850°F - 4 Hrs.	Allegheny Ludlum	Sheet	Long.	50	287.5	284.7	4.5	
						Trans.	50	302.9	300.6	4.0	
			CW + Refrig. + 850°F - 4 Hrs.		Sheet	Long.	50	282.0	279.2	4.0	
						Trans.	50	302.5	298.4	3.0	
			CW + Refrig. + 900°F - 4 Hrs.		Sheet	Long.	50	284.4	280.0	3.0	
						Trans.	50	303.3	294.4	2.5	
			1500°F-10 Min + Refrig. + 850°F - 4 Hrs.		Sheet	Long	0	263.6	256.2	6.0	
						Trans.	0	249.2	260.9	4.5	
23311	5000	Air induction Consutrode Remelt	CW + 850°F - 4 Hrs.	Allegheny Ludlum	Sheet	Long.	50	274.6	274.6	4.0	
						Trans.	50	290.4	283.1	3.5	
			CW + Refrig. + 850°F- 4 Hrs.		Sheet	Long.	50	275.5	274.7	4.0	
						Trans.	50	285.0	276.9	3.5	
			1550°F-10 min + Refrig. + 850°F-4 Hrs.		Sheet	Long.	0	254.9	237.9	5.0	
						Trans.	0	260.5	254.0	5.0	
23222*	5000	Air induction Consutrode Remelt	1500°F-10 min + Regrig + 850°F-4 Hrs.	Allegheny Ludlum	Sheet	Long.	0	255.9	246.2	7.0	
			1500°F-10 min + C.W + Refrig. + 850°F-4 Hrs.		Sheet	Trans.	25	256.8	254.4	4.0	
						Trans.	25	213.2	212.7	4.0	
						Long.	25	269.7	269.6	4.5	
						Long.	25	273.8	264.7	5.0	
						Trans.	50	281.4	278.6	1.0	
						Trans.	50	284.7	284.4	2.0	
						Long.	50	285.6	283.6	3.5	
						Long.	50	289.6	286.9	3.5	
						Trans.	75	305.5	305.5	2.0	
						Trans.	75	304.4	304.4	0.5	
						Long.	75	301.7	300.0	1.5	
						Long.	75	294.9	292.6	2.0	
						Trans.	80	303.4	300.8	0.5	
						Trans.	80	305.9	303.9	0.5	

* Curtiss Wright Corporation data on this heat has been previously reported in tables XIII, XIV, XV, XVI, XVII of Progress Report No. 1.

TABLE 82

TENSILE PROPERTIES OF LARGE 20% NICKEL HEATS MELTED BY THE ALLEGHENY LUDLUM STEEL CORPORATION

Heat Number	Size of Heat (lbs)	Melting Method	Heat Treatment	Data Source	Specimen Form	Direction	% Cold Reduct.	UTS KSI	.2% YS KSI	Elong. %	R.A. %
						Long.	80	295.9	294.8	1.0	
						Long.	80	304.4	302.1	1.0	
10393	1000	Air induction Consutrode Remelt	900°F-4 Hrs.	Allegheny Ludlum	Bar	-	-	301.2	289.2	11	51.2
								296.2	277.1	13	48.3
			Refrig. + 900°F-4 Hrs.		Bar	-	-	293.1	280.1	12	48.3
			1500°F-1 Hr. + Refrig. + 900°F-4 Hrs.		Bar	-	-	292.2	271	8	20.8 *
								289.2	265	8	13.6
			1500°F-1 Hr. + Refrig. + 900°F-4 Hrs.		Bar	-	-	304.2	283.1	6	25.1
								301.2	283.1	8	27.7

* Largo Grain Size

TABLE 83

TENSILE PROPERTIES OF LARGE 20% NICKEL HEATS MELTED
BY THE CARPENTER STEEL CORPORATION

Heat Number	Size of Heat (lbs.)	Melting Method	Heat Treatment	Data Source	Specimen Form	Direction	% Cold Reduction	UTS KSI	.2% YS KSI	Elong. %	R.A. %	Notch Tensile KSI
K15382	2000	Air Induction Consutrode Remelt	1500°F - 30 Min. + 900°F - 2 Hrs.	Carpenter Steel	Bar			265.5 263	252.5 -	3 3.3	26 21	
			1500°F - 5 Min. + 900°F - 2 Hrs.		Bar			271.5 270.5	258 -	6.6 7.5	57.7 56.1	
			1500°F - 15 Min. + 900°F - 2 Hrs.		Bar			285.4 277.0	264.0 267.3	6.5 6.1	57.7 57.9	
			1500°F - 2 Hrs. - AC + 1500°F - 30 Min. + 900°F - 2 Hrs.		Bar			271.9 272.7	260.2 261.3	6.4 6.5	58.9 57.9	
			1700°F - 2 Hrs. - AC + 1500°F - 30 min. + 900°F - 2 Hrs.		Bar			272.2 269.3	258.7 -	6.6 5.0	55.7 42.8	
			1900°F - 2 Hrs. - AC + 1500°F - 30 Min. + 900°F - 2 Hrs.		Bar			269.4 268.9	255.7 -	4.7 5.0	40.4 37.8	
			1500°F - 15 Min. + Refrig. + 850°F - 4 Hrs.		Bar			270.5 274.5	258 -	- 1.2	57.7 59.7	
			1500°F - 1 Hr. + Refrig. + 850°F - 1 Hr.	INCO	Bar			267	255	12	57	231
			1500°F - 1 Hr. + Refrig. + 850°F - 4 Hrs.		Bar			270	261	12	57	318
			1500°F - 1 Hr. + Refrig. + 900°F - 1 Hr.		Bar			264	251	13	60	-

TABLE 83

TENSILE PROPERTIES OF LARGE 20% NICKEL HEATS MELTED
BY THE CARPENTER STEEL CORPORATION

Heat Number	Size of Heat (lbs.)	Melting Method	Heat Treatment	Data Source	Specimen Form	Direction	% Cold Reduction	UTS KSI	.2% YS KSI	Elong. %	R.A. %	Notch Tensile KSI
K15382	2000	Air Induction Consutrode Remelt	1500°F - 1 Hr. + 850°F - 1 Hr.	INCO	Bar			270	254	12	57	318
			1500°F - 1 Hr. + 850°F - 4 Hrs.		Bar			270	258	12	57	353
			1500°F - 1 Hr. + 900°F - 1 Hr.		Bar			265	251	14	59	-
			1500°F - 15 Min. + Refrig. + 850°F - 1 Hr.		Bar			266	254	14	59	320
			1500°F - 15 Min. + Refrig. + 850°F - 4 Hrs.		Bar			281	270	11	54	361
			1500°F - 15 Min. + Refrig. + 900°F - 1 Hr.		Bar			271	260	13	53	366
			1500°F - 15 Min. + 850°F - 1 Hr.		Bar			266	254	14	59	320
			1500°F - 15 Min. + 850°F - 4 Hrs.		Bar			281	270	11	54	361
			1500°F - 15 Min. + 900°F - 1 Hr.		Bar			281	272	12	56	349
			1500°F - 15 Min. + Refrig. + 850°F - 1 Hr.		Bar			281	276	11	54	359
			1500°F - 15 Min. + Refrig. + 850°F - 4 Hrs.		Bar			273	268	11	54	339

TABLE 83

TENSILE PROPERTIES OF LARGE 20% NICKEL HEATS MELTED BY THE CARPENTER STEEL CORPORATION

Heat Number	Size of Heat (lbs.)	Melting Method	Heat Treatment	Data Source	Specimen Form	Direction	% Cold Reduction	UTS KSI	.2% YS KSI	Elong. %	R.A. %	Notch Tensile KSI
K15382	2000	Air Induction Consutrode Remelt	1500°F - 15 Min. + Refrig. + 900°F - 1 Hr.	INCO	Bar			268	264	11	54	370
V11929	1500	Vacuum Induction	1500°F - 30 Min. + 950°F - 2 Hrs.	Carpenter Steel	Bar			279.2 277.8	259.9 -	3.8 3.9	29.2 28.6	

TABLE 84

PROPERTIES OF RECENT PRODUCTION 20% NICKEL ALLOY HEATS

Heat No.	Size of Heat (lbs)	Melting Method	Heat Treatment	Data Source	Specimen Form	U.T.S. KSI	0.2% Y.S. KSI	% Elong. in 4D or 2"	% R.A.
K-51888	28000	Air Arc-Consumable Electrode Remelt	1500°F-15 min +900°F- 2 hrs	Carpenter Steel Company	Bar from Pancake	258.5 259.2	- 248.2	6.2 7.1	23.6 23.7
			1500°F- 1 hr +900°F- 2 hrs			257.5 256.7	- 244.5	6.1 6.2	22.7 22.3
23710	1000	Air Induction -Consumable Electrode Remelt	1500°F-15 min +850°F- 4 hrs	Inco	Bar	290	283	10	50.5
			850°F- 4 hrs			288	279	15	53
40058	4000	Air Arc-Consumable Electrode Remelt	1500°F- 1 hr +900°F- 3 hrs	Latrobe	Bars, Transverse from 10" RCS	262.4 263.3 271.0	251.2 254.2 256.1	13 12 14	55 53 51

TABLE 45

COMPOSITION OF PRODUCTION 25% NICKEL ALLOY HEATS

	Mat'l.	Producer	Heat No	Size Of Heat	Melting Method	Chemistry C	Mn	P	S	Si	Ni	Ti	Al	Cb	B	Zr	Ca	Fe
1)	25% Nickel	Special Metals, Inc. (formerly Kelsey-Hayes, Corp., Metals Div.)	52593	1000	Vacuum Induction	0.03	$<$0.1	-	-	$<$0.1	24.92	1.70	0.22	0.39	NA	NA	NA	Bal
2)	25% Nickel	Special Metals, Inc.	52594	1000	Vacuum Induction	0.03	$<$0.1	-	-	$<$0.1	24.60	1.73	0.22	0.38	NA	NA	NA	Bal
3)	25% Nickel	Allegheny Ludlum Corp.	23220	5000	Air Induction Consutrode remelt	0.015	0.10	0.007	0.002	0.14	25.18	1.72	0.04	-	NA	NA	NA	Bal
4)	25% Nickel	Allegheny Ludlum Corp.	23314	5000	Air Induction Consutrode remelt	0.008	0.13	0.001	0.002	0.07	25.40	1.44	0.26	0.42	NA	NA	NA	Bal

NA - Not Analysed

TABLE 85

COMPOSITION OF PRODUCTION 25% NICKEL ALLOY HEATS

	Mat'l.	Producer	Heat No.	Size Of Heat	Melting Method	Chemistry C	Mn	P	S	Si	Ni	Ti	Al	Cb	B	Zr	Ca	Fe
5)	25% Nickel	Allegheny Ludlum Corp.	23315	5000	Air Induction Consutrode remelt	0.010	0.18	0.006	0.003	0.02	25.65	1.65	0.26	0.43	NA	NA	NA	Bal
6)	25% Nickel	Allegheny Ludlum Corp.	23223	5000	Air Induction Consutrode remelt	0.006	0.12	0.008	0.002	0.17	25.33	1.37	0.20	0.54	NA	NA	NA	Bal.
7)	25%	Special Metals Inc.	7552	5000	Vacuum Induction Consutrode remelt	<0.03	<0.05	<0.05	<0.01	<0.01	25.75	1.51	0.25	0.50	NA	NA	NA	Bal.

TABLE 86

TENSILE PROPERTIES OF LARGE 25% NICKEL HEATS MELTED BY ALLEGHENY LUDLUM STEEL CORPORATION

Heat No	Size Of Heat (lbs)	Melting Method	Heat Treatment	Data Source	Specimen Form	Direction	% Cold Reduction	U.T.S. KSI	.2% YS KSI	Elong %	RA %	Notch Strength KSI (Kt 10-12)
23223*	5000	Air Induc Consu-trode Remelt	1500°F-10 Min AC, Cold rolled to indicated amount, 16 hrs. @ -100°F, Aged 850°F -4 hrs.	Allegheny Ludlum	.125 Sheet	Long.	0	265.9	257.5	6.0	-	
					Sheet .116	Trans.	25	259.7	236.1	8.0	21.6	
					Sheet .116	Trans.	25	244.4	227.4	4.0	21.7	
					Sheet .115	Long.	25	264.5	250.6	5.0	21.6	
					Sheet .116	Long.	25	262.6	248.0	5.0	21.6	
					Sheet .077	Trans.	50	269.6	250.0	3.0	21.4	
					Sheet .076	Trans	50	275.3	255.7	1.0	21.3	
					Sheet .074	Long	50	270.0	261.7	4.0	21.9	
					Sheet .075	Long	50	275.4	262.1	4.0	22.6	
					Sheet .039	Trans	75	294.8	286.0	2.0	25.6	
					Sheet .039	Trans	75	281.5	280.9	0.5	24.8	
					Sheet .037	Long	75	291.8	289.6	2.0	24.7	
					Sheet .037	Long	75	289.6	285.5	2.0	24.4	
					Sheet .025	Trans	83	301.6	301.6	0.5	27.4	
					Sheet .025	Trans	83	305.2	305.2	1.0	27.1	
					Sheet .024	Long	83	293.9	293.9	0.5	27.8	
					Sheet .023	Long	83	302.1	300.4	1.5	-	
			1500°F - 1 Hr + 1300°F - 4 Hrs + Refrig + 800°F - 1 Hr.	INCO	Bar	--	--	265	249.5	12	53	306
			1500°F - 1 Hr + 1300°F - 4 Hrs + Refrig + 850°F - 1 Hr	INCO	Bar	--	--	279	265	12	52	279
					"	--	--	266	252	11	52	283
					"	--	--	267	253	11	53	296
					"	--	--	270	258	12	55	-
					"	--	--	268	251	12	54	284
			1500°F - 1 Hr + 1300 - 4 Hrs + Refrig + 850°F - 1 Hr + 300°F - 16 Hrs	INCO	Bar	--	--	268	248	11	53	275
					"	--	--	265	252	11	53	316

TABLE 86

TENSILE PROPERTIES OF LARGE 25% NICKEL HEATS
MELTED BY ALLEGHENY LUDLUM STEEL CORPORATION

Heat No	Size Of Heat (lbs)	Melting Method	Heat Treatment	Data Source	Specimen Form	Direction	% Cold Reduction	U.T.S KSI	.2% YS KSI	Elong %	RA %	Notch Strength KSI (Kt 10-13)
			1500°F - 1 Hr + 1300°F - 4 Hrs + Refrig + 900°F - 1 Hr	INCO	Bar	--	-	279	268	12	51	238
			1500°F - 1 Hr + 1150°F -16 Hrs + Refrig + 800°F - 1 Hr	INCO	Bar	--	-	319	284	8	28	216
			1500°F - 1 Hr + 1150°F -16 Hrs + Refrig + 850°F - 1 Hr	INCO	Bar	--	-	321	268	8	28	183
			1600°F - 1 Hr + 60% CW + Refrig + 850°F - 1 Hr	INCO	Bar	--	-	-	-	-	-	366
23223*	5000	Air Induc. Consutrode Remelt	1600°F - 1 Hr + 60% CW + Refrig. + 900°F - 1 Hr.	INCO	Bar	--	60	279	270	13	58	361
			1600°F - 1 Hr + 80% CW + Refrig. + 900°F - 1 Hr.	INCO	Bar	--	80	286	276	12	57	-

*Curtiss-Wright data on this heat has been previously reported in Tables II, III, IV, V, VI and IX of Progress Report No. 1

Heat No	Size Of Heat (lbs)	Melting Method	Heat Treatment	Data Source	Specimen Form	Direction	% Cold Reduction	U.T.S KSI	.2% YS KSI	Elong %	RA %	Notch Strength KSI (Kt 10-13)
23220	5000	Air Induction Consutrode Remelt	1500°F - 10 min + Refrig. + 850°F - 4 Hrs.	Allegheny Ludlum	Sheet	Long.	0	248	240	3.0	-	
			1500°F - 10 min + CW + Refrig. + 850°F - 4 hrs.		Sheet	Trans.	50	278	267.9	3.0	-	
23314	5000	Air Induction Consutrode Remelt	CW + 900°F - 4 hrs.	Allegheny Ludlum	Sheet	Long	50	254.9	215.1	4.5		
						Long	50	242.6	208.3	4.5		
						Trans	50	247.5	209.4	4.5		
						Trans	50	253.8	217.3	4.5		
			CW + Refrig. + 900°F - 4 Hrs		Sheet	Long	50	264.0	248.8	3.5		
						Long	50	267.4	253.2	3.5		
						Trans.	50	280.3	264.8	1.5		
						Trans.	50	276.0	256.6	4.0		
			CW + 900°F - 4 Hrs.		Sheet	Long	50	241.6	210.1	4.5		
						Trans	50	246.1	216.7	3.5		
			CW + Refrig + 900°F - 4 Hrs		Sheet	Long	50	281.0	266.7	4.0		
						Trans	50	291.5	271.0	3.5		

TABLE 30

TENSILE PROPERTIES OF LARGE 25% NICKEL HEATS
MELTED BY ALLEGHENY LUDLUM STEEL CORPORATION

Heat No	Size Of Heat (lbs)	Melting Method	Heat Treatment	Data Source	Specimen Form	Direction	% Cold Reduction	U T S KSI	2% YS KSI	Elong %	RA %	Notch Strength KSI (Kt 10-12
			CW + 1300°F - 4 Hrs + Refrig + 900°F - 4 Hrs		Sheet	Long	50	257 8	247 7	4 0		
						Trans	50	279 4	267 8	2 0		
			1550°F - 10 Min + 1300°F - 4 Hrs + Refrig + 900°F - 4 Hrs		Sheet	Long	0	260 7	241 2	4.5		
						Trans	0	263 5	248 0	4 0		
23315	5000	Air Induction Consutrode Remelt	CW + 900°F - 4 Hrs	Allegheny Ludlum	Sheet	Long	50	219 9	178 7	5 0		
						Long	50	223.9	179 2	4.0		
						Trans	50	229 3	176 3	4 0		
						Trans	50	232 1	181 2	4 0		
			CW + Refrig. + 900°F - 4 Hrs		Sheet	Long	50	25[illegible] 9	237 2	2 0		
						Long	50	259 2	238.1	4 0		
						Trans	50	267 [illegible]	247 [illegible]	3 5		
						Trans	50	267.9	243 3	2 0		
23315	5000	Air Induction Consutrode Remelt	CW + 900°F - 4 Hrs	Allegheny Ludlum	Sheet	Long	50	219.2	202 1	5 0		
						Trans	50	220 1	183 4	3 5		
			CW + Refrig + 900°F - 4 Hrs		Sheet	Long	50	274 5	254.[illegible]	3 8		
						Trans	50	281.0	258 [illegible]	3.5		
			1500°F - 10 Min + 1300°F - 4 Hrs + Refrig. + 900°F - 4 Hrs		Sheet	Long	0	243 7	2[illegible]9 9	4 5		
						Trans	0	246 9	229 5	4.0		
			CW + 1300°F - 4 Hrs + Refrig. + 900°F - 4 Hrs		Sheet	Long	50	264 4	264 4	3.5		
						Trans	50	272.5	263.0	4 0		

TABLE 87

TENSILE PROPERTIES OF LARGE 25% NICKEL HEATS MELTED BY SPECIAL METALS INCORPORATED

Heat Number	Size Of Heat Lbs	Melting Method	Heat Treatment	Data Source	Specimen Form	Direction	UTS KSI	.2% YS KSI	Elong. %	R. A. %
52593	1000	Vacuum Induction	1600^oF - 1 hr., 50% CW Refrig - 100^oF - 1½ hrs. age 850^oF - 1 hr.	Curtiss Wright	.100 Sheet	Long	282	268	3.5	25
			1500^oF - 1 hr., 50% CW Refrig - 100^oF 16 hrs. age 850^oF - 1 hr.	Special Metals	.040 Sheet	Long	280	275	-	-
			1500^oF - 1 hr. - 1300^oF - 4 hrs. 950^oF - 1 hr.	Special Metals	.060 Sheet	Long Trans	269 272	243 240	- 5.5	-
			1500^oF - 1 hr. - 1300^oF 4 hrs - Refrig. - 100^oF 16 Hrs age 850^oF - 1 hr.	Special Metals	3/4" D Bar		279	264	11	42
52594*	1000	Vacuum Induction	1500^oF - 1 hr. - 50% CW Refrig - 100^oF 16 hrs. age 850^oF - 1 hr.	Special Metals	3/4" D Bar		301	291	10	39
			1500^oF - 1 hr. - 1300^oF 4 hrs. - Refrig. - 100^oF - 16 hrs. - Age 850^oF - 1 hr.	Special Metals	3/4" D Bar		280	262	9	34

*Curtiss-Wright Corporation data on this heat has been previously reported in Tables VII, and VIII of Progress Report No. 1.

7552*	5000	Vacuum Induction Consutrode Remelt	1500^oF - 1 hr. - 1300^oF 4 hrs. Refrig. - 100 16 Hrs. Age 900^oF 1 hr.	Special Metals	Bar		275	259	-	-

*Relatively new heat, not fully evaluated.

2.0 20% NICKEL ALLOY

The effects of heat treating parameters on solution annealed, cold worked and warm worked 20% nickel were evaluated in detail. Results of this work are discussed in the following sections.

2.1 Solution Annealed Condition

2.1.1 Effect of Solution, Refrigeration and Maraging Parameters on Hardness

The effects of various solution temperatures and times on hardness are presented in Figure 156 and tabulated in Table 88. Figure 156 illustrates that temperatures below 1500°F and even 1500°F for ¼ hour are insufficient for attaining adequate solutioning based upon solution treated hardness. However, the fine grained microstructure of the alloy remaining after the 1400°F solution treatment appeared promising. Further study of solution temperature and time was performed by evaluating temperatures ranging from 1400°F to 1600°F at 50°F increments.

The effects of maraging temperature and time were determined by holding solution temperature and time fixed at 1500°F for 1 hour. Maraging temperatures between 800°F and 950°F were evaluated. Times from ¼ hour to 10 hours for each temperature were studied. The hardness response curves are reported in Table 89 and Figure 157. Basically, the curves indicate little variation in hardness regardless of maraging temperature and time. Rockwell hardness is not sensitive enough to accurately indicate peak response. It does, however, bracket the general maraging range.

2.1.2 Effect of Solution Parameters on Sheet Tensile Properties

The effects of solution parameters on the longitudinal and transverse tensile properties are reported in Tables 90 and 91. Longitudinal data are plotted in Figure 90 and transverse data in Figure 91. Both longitudinal and transverse strengths peak out for solution temperature between 1550°F and 1600°F. The longitudinal yield strength peaks at 270 KSI for a 1550°F solution temperature. Ductility peaks for a 1600°F solution temperature with a corresponding slight decrease in longitudinal yield strength to 265 KSI. Consequently, the trade off in yield strength for the gain in ductility is preferable.

2.1.3 Effect of Solution Parameters on the Fracture Toughness

The effect of solution treatment on the longitudinal and transverse

fracture toughness is reported in Tables 92 and 93. Figure 160 presents the fracture toughness parameter K_c as a function of solution temperature and time. It is evident from the preceding section that as solution temperature increases, strength increases but fracture toughness decreases. For 1400°F, an average longitudinal K_c value of 185 KSI in was obtained, representing a yield strength of 227 KSI. For 1600°F the average K_c value dropped to 90 KSI in for a corresponding yield strength of 265 KSI.

2.1.4 Effect of Maraging Parameters on the Tensile Properties of Solution Treated 20% Nickel Alloy

Tables 90 and 91 report the effect of maraging parameters on the longitudinal and transverse tensile properties in combination with various solution temperatures and times. A review of tensile data versus fracture toughness as a function of solution temperature, time and maraging temperature and time revealed that the best combination of strength, ductility and toughness was obtained by a 1450°F/1 hour solution treatment and 900°F/10 hours marage. This treatment produced an average longitudinal yield strength of 255 KSI and K_c value of 136.5 KSI $\sqrt{in.}$

2.1.5 Effect of Maraging on Fracture Toughness

As reported in Tables 92 and 93, a solution temperature of 1450°F/1 hour and maraging temperature of 900°F/10 hours produced the best combination of strength and toughness. A 1400°F/1 hour solution treatment followed by a 900°F/10 hour marage yielded average longitudinal K_c values of 153 KSI $\sqrt{in.}$ However, yield strength was low, averaging 227 KSI.

2.2 Cold Work Condition

2.2.1 Effect of Cold Work on Tensile Properties

Effect of cold work and maraging parameters on the 20% nickel alloy in the longitudinal and transverse rolling directions are presented in Tables 94 and 95. Figure 161 illustrates yield strength of cold worked 20% nickel alloy as a function of the Larson-Miller parameter "P". The maximum yield strength response is obtained at a parameter level of 28 (900°F/3 hours) for 30% cold worked material. However, examination of Table 94 indicates that the best combination of strength and ductility is achieved by a 900°F/10 hour marage regardless of cold work levels.

2.2.2 Determination of Optimum Maraging Parameters and Cold Work

Optimization of longitudinal yield strength response was performed by construction of the three dimensional graph shown in Figure 162. The optimum yield strength response surface is shown to lie between parameter boundaries of 27.7 and 28.5. The strength peak for 30% cold worked material is at 307 KSI for a parameter level of 28 (900°F-3 hours). Material cold worked 50% peaks at 305 KSI.

2.2.3 Effect of Cold Work on the Fracture Toughness

Longitudinal and transverse fracture toughness parameters as a function of cold work level and maraging parameters are reported in Tables 196 and 197. The data have been interpreted in terms of average K_c values and plotted in Figure 163.

Fracture toughness K_c values are all below the 150 KSI $\sqrt{\text{in.}}$ level regardless of cold work level or heat treatment since only treatments which produced good yield strength were evaluated. Fracture toughness for cold worked material falls with increasing degree of work. At the 20% cold work level, longitudinal K_c values range from 138 to 147 KSI $\sqrt{\text{in}}$. At 50% cold work level, the K_c values have dropped to the range of 105 to 128 KSI $\sqrt{\text{in}}$. The span of K_c values follows the trend established by tensile properties of cold worked material. Increasing cold work level did not drastically affect strength as shown in Figure 161.

2.3 Warm Worked Condition

2.3.1 Effect of Warm Work on the Tensile Properties

The longitudinal and transverse tensile properties of 20% nickel alloy warm worked at 1200°F, 1400°F and 1600°F and maraged at 900°F for various times are reported in Tables 98 and 99. The data are plotted in Figures 164 and 165 as a function of the Larson-Miller parameter. As shown in the figures, maximum response was exhibited by material warm worked at 1400°F and maraged at 900°F for 3 to 10 hours for both the longitudinal and transverse directions. Yield strength averaged from 268 to 277 KSI for the above maraging treatments.

Optimization of longitudinal yield strength response was performed by plotting warm working temperature against Larson-Miller parameter in three dimensional form, shown in Figure 166. The yield strength response surface developed between the 1400°F and 1600°F warm working temperatures indicates a peak yield strength of 277 KSI for the 1400°F warm working at a Larson-Miller parameter of 27.8 (900°F/3 hours).

The yield strength response boundary lies between a "P" of 27.5 and 28.56.

2.3.2 Effect of Warm Work on Fracture Toughness

Table 100 reports the effect of warm working temperature and maraging parameters on fracture toughness parameters for longitudinal and transverse rolling directions. Figure 167 illustrates the behavior of the fracture toughness parameter K_c as a function of warm working temperature for a maraging treatment of 900°F/10 hours. It is shown that warm working at 1200°F produced the greatest K_c value, 215 KSI $\sqrt{in}$ to accompany the low yield strength of 206 KSI. Toughness falls rapidly with increased warm working temperature. The K_c value for a warm working temperature of 1400°F was 114 KSI $\sqrt{in}$ for a yield strength value of 262 KSI. As warm working temperature was increased to 1600°F, K_c increased to 143 KSI $\sqrt{in}$ for a correspouding yield strength of 255 KSI. Consequently, although yield strength is lowered, the 1600°F warm working temperature exhibited a 30 KSI $\sqrt{in}$ improvement in K_c value.

2.4 Miscellaneous Properties

2.4.1 Elevated Temperature Properties

The elevated temperature tensile properties of the 20% nickel alloy are presented in Figure 168. Tensile strengths fall rather abruptly with increasing test temperature. At 250°F, yield strength was 242 KSI. At 750°F, the yield strength had fallen to 205 KSI. A more rapid drop occurred when the temperature increased from 750°F to 1000°F where a yield strength of 123 KSI was determined.

Ductility remained relatively constant at approximately 10% elongation and 50% reduction of area until test temperatures exceeded 750°F. At 1000°F, elongation measured 20% and reduction of area 70%.

2.4.2 Heat Treat Response of a Thick Section

A 4½" x 4½" x 5½" long billet was solution treated at 1450°F/1 hour/inch of section and subsequently maraged at 900°F/10 hours/inch of section to determine heat treat response as a function of thickness. Table 101 reports the results obtained from specimens removed from the surface versus the center of the billet. As indicated, all but one specimen which was removed from the surface, failed in a brittle manner. Figure 169 presents the comparison of ultimate strengths and ductility between surface and center billet specimens. It is quite apparent that although center billet heat treat response was indicative of excellent hardenability (as shown by hardness and the ultimate

strength of 227 KSI) ductility for both areas was indicative of insufficient billet conditioning. Unlike the 18% nickel alloys, the 20% nickel alloy appears to require increased conditioning in order to produce a homogeneous structure in heavy sections.

2.4.3 Effect of Forging Reduction on Tensile Properties

Similarly to the manner described for both 18% nickel alloys, the effect of forging reduction on bar tensile properties as a function of direction and location within the forging was evaluated. Specimens removed were heat treated at 1450°F/1 hour and 900°F/10 hours. Table 102 presents a tabulation of the results obtained. Figures 170 through 173 present tensile properties for each location and direction from which specimens were removed as a function of forging reduction. Inspection of the figures reveals that vertical edge specimens exhibited superior strength when compared with vertical center specimens. Ductility was also superior for all reductions. The indications are again that the billet did not receive thorough conditioning. As degree of forging reduction increased, the vertical center specimens became increasingly less ductile although additional hot working and consequently homogenization was accomplished. Evidently, the lack of internal billet conditioning and lack of center material breakdown encountered in the direction normal to applied forging force, produced the poor ductility.

A similar condition to that described above was determined to exist with horizontal specimens removed from the center of the disc, but to a greater extent. Except for specimens from a forging representing 33.8% reduction, no yield strength or ductility measurements were possible since brittle failures occurred.

The results of this work have indicated the necessity of very thorough conditioning of the 20% nickel alloy billets to achieve the desired mechanical properties.

2.4.4 Fatigue Properties

The R. R. Moore Rotating Beam, fatigue endurance strengths of solution and maraged (1450°F/1 hour - maraged at 900°F/10 hours) and 30% cold worked (maraged 900°F/10 hours) were determined by generating the S-N curves shown in Figures 174 and 175, respectively. The specimen "run outs" indicate both solution treated and 30% cold worked 20% nickel alloy to have similar endurance strengths of 86,000 and 80,000 psi, respectively. Apparently, the ductility of the alloy in the studied conditions, affects the fatigue properties similarly to low alloy steels at high hardness levels which are past the peak endurance strength. However, this opinion is an assumption, at best, consider-

ing the amount of existent data.

2.4.5 Impact Properties

Charpy impact strength at room and cryogenic temperatures for solution annealed (1450°F/1 hour, maraged at 900°F/10 hours) and cold worked (30 and 40% cold work, maraged at 900°F/10 hours) are reported in Figures 176 and 177, respectively. Room temperature impact strengths for all conditions lie between 10 to 15 ft-lbs. As test temperature decreases, impact strength decreases moderately. At -300°F, solutioned material exhibits 7 ft-lbs and both cold work levels 4.5 ft-lbs. Generally, the moderate ductility shown by the alloy was again witnessed in the form of disappointing impact values.

2.5 Summary Discussion

A comparison of fracture toughness parameters representing various 20% nickel alloy conditions is presented in Table 103. It is shown that all barstock conditions produced surprisingly similar toughness properties. The notch tensile to ultimate strength ratio for solutioned bar stocks is 1.27 to 1.43 versus 1.11 to 1.17 for cold worked bar stock. However, the similarity of notch tensile strength immediately reveals that the variation in the ratio is caused by lower ultimate strength of solutioned material.

Figure 178 presents a comparison of K_c values of annealed and cold worked material as a function of yield strength level. Cold worked material, although at a higher yield strength level (300 KSI) produced, in general, higher K_c values (100 to 148 KSI $\sqrt{in}$). Solutioned specimens at yield strengths of approximately 265 KSI produced K_c values of 83 to 120 KSI $\sqrt{in}$.

The strengths, ductility and toughness values determined for the 20% nickel heat studied were disappointingly low. It is deduced that the low results are applicable only to this heat since data generated by other sources on various heats has been excellent.

The structures of 20% nickel in the solutioned and solutioned and aged conditions are presented in Figure 179. The martensitic structure after a 1500°F/1 hour solution treatment is obscured by the precipitation of γ', Ni_3 (Al, Ti) and the grain boundary precipitate of Fe_2Ti produced by a 900°F/10 hr. marage. Also detected in the electron micrographs are small voids left after removal of spherical particles, probably oxides or nitrides formed from the additions of deoxidizing elements.

2.6 Weld Properties

Hardness and tensile properties for the 20% nickel alloy welded in both the solution heat treated and cold worked conditions using various filler materials are presented in the following sections. A comparison of filler materials based on weld fracture toughness is also included.

2.6.1 - Hardness Properties

Weld Zone

Vertical hardness traverses taken along the vertical weld centerline for four different filler wires, the 18% nickel (250 KSI) and three modified 20% nickel compositions, are given in Table 104 and Figure 180. After maraging at 850°F/4 hours, the fusion pass area of the weld was about 3 R_c higher in hardness than the filler wire deposit area in all cases examined (Figure 180). A similar aged hardness of 46 to 48 R_c was noted for all filler wire deposits tested (Figure 180). Longitudinal weld hardnesses taken between the weld centerline and the weld-base metal interface showed a similar hardening response, Table 104.

Heat-Affected-Zone

Longitudinal hardness surveys taken in weld heat-affected-zones between the weld-base metal interface and a point in the unaffected base material are presented in Table 105 and Figures 181 and 182.

As shown in the as-welded plot in Figure 181, the heat-affected-zone of solution heat treated material experienced rather vigorous aging in an area approximately 0.175" from the weld interface. Hardness was increased from 36 to 51 R_c in this area. This aging behavior was similar to that reported for the 18% nickel alloys. Hardness across the heat-affected-zone of the 20% nickel alloy after aging was not as uniform (Figure 181), as was the solution heat treated 18% nickel alloys. After maraging, hardness was approximately 50 R_c in the area resolutioned during welding, as compared to 53 to 54 R_c in the area aged initially during welding.

The heat-affected zone of cold worked material was aged to about 55 R_c during welding in approximately the same area as solution heat treated sheet. (Figure 182). The area adjacent to the weld interface was softened by resolutioning to a hardness of about 30 R_c from a level of 45 R_c in unaffected base material. As previously observed in the 18% nickel alloys, this area hardened to about 52 R_c as compared to 55 R_c in unaffected base material after aging (Figure 182).

2.6.2 Tensile Properties

In this section the evaluation of welding filler materials is based upon the results of transverse weld tensile tests made with the sheet rolling direction parallel to the test direction. Weld joint efficiencies used for comparison purposes were calculated on the same basis as previously described for the 18% nickel alloy in Section 5.2.6.2. They are included in Table 9.

Solution Heat Treated Base Material (0.140" Sheet)

The results of transverse weld tensile tests comparing various filler wire compositions are shown in Table 107 and Figure 183. Preliminary tests were made using a maraging treatment of 850°F for 4 hours. Test results revealed that welds made with three of the four wires evaluated (the 18% nickel (250 KSI) wire and both molybdenum containing 20% nickel wires) all exhibited yield strengths of approximately 222 KSI. (Figure 183). However, the level of weld yield strength joint efficiency (84%) attained was rather low.

Welds made using the molybdenum-free modified 20% nickel steel filler wire demonstrated extremely poor tensile properties, as shown in Table 107. These welds failed in a brittle fashion as evidenced by a yield strength joint efficiency of 67% and reduction in area of only 3% (Table 107). On the basis of the preliminary test results, this filler wire was not evaluated further.

Transverse weld tensile properties were vastly improved when a maraging treatment of 10 hours at 900°F was used (Table 107 and Figure 183). Yield strength joint efficiencies were increased to 98-102%, and a maximum average yield strength of 256 KSI was attained in welds made with the modified 20% nickel + Mo wire.

In these tests, weld ductility was also substantially improved, which suggested that the 850°F treatment might have a slightly embrittling effect on weld deposits. The marked increase in weld strength did not follow the same behavior demonstrated by unwelded solution heat treated and aged 20% nickel alloy sheet. As shown in Table 90, unwelded sheet yield strength is lower for the 900°F/10 hour marage as compared to 850°F/4 hours.

Solution Heat Treated Base Material (0.070" Sheet)

Transverse tensile properties of welds in 0.070" thick sheet maraged 900°F/10 hours are presented in Table 108 and Figure 184. The majority of tensile specimens from these welds failed in a brittle fashion. Examination revealed that fracture paths traversed both

weld and heat-affected-zone in the area adjacent to the weld fusion line (Table 108). This behavior was found to be independent of the filler wire used. As a result, average weld strength and ductility were generally lower than reported for corresponding welds in 0.140" sheet (Tables 107 and 108).

50% Cold Worked Base Material (0.140" Sheet)

Results of transverse tensile tests made on welds produced in cold worked sheet are given in Table 109 and Figure 185. Preliminary tests using a maraging treatment of 850°F for 4 hours were made only on welds produced with the 20% nickel, molybdenum containing wire. The relatively low yield strength of 221 KSI which resulted, was about the same as obtained for a corresponding weld in solution heat treated sheet (Table 107). After maraging at 900°F for 10 hours, a maximum average yield strength of 260 KSI (89% joint efficiency) was attained in the weld made with the 18% nickel (300 KSI) wire.

Little change in yield strength was observed between welds produced in cold worked as compared to solution heat treated sheet using either molybdenum containing 20% nickel wires (7C-059 and 7C-060). Average yield strengths for a marage of 900°F/10 hours varied between 245 and 248 KSI for the 7C-060 wire welds and 250 and 256 KSI for the 7C-059 wire welds (Tables 109 and 107).

2.6.3 Fracture Toughness

Fracture toughness of welds made using the various filler materials are given in Table 110. The results are compared graphically on the basis of K_c values in Figure 186. All specimens were maraged at 900°F for 10 hours.

As shown in Figure 186, a high level of fracture toughness was achieved in welds made with four different filler wires, particularly the 18% nickel (250 KSI) and the 20% nickel, molybdenum containing alloys. Average weld fracture toughness values (K_c) varied from 128 to 174 KSI$\sqrt{in.}$ It is of particular significance that the majority of these toughness values exceeded even longitudinal fracture toughness (137 KSI$\sqrt{in}$) reported for unwelded base material (solution treated 1450°F and maraged 900°F/10 hours) in Table 92. They far exceeded transverse sheet fracture toughness K_c values of 75 KSI$\sqrt{in.}$ given in Table 93. Maximum K_c weld toughness values of 162-185 KSI$\sqrt{in.}$ were obtained using the 18% nickel (250 KSI) filler wire. The excellent weld fracture toughness of this filler wire was previously demonstrated in welds in the 250 KSI alloy (Table 40).

2.6.4 Summary

On the basis of welding studies made in this investigation, the 20 percent nickel alloy was found to possess good weldability, but only in the 0.140" thick sheet.

Transverse tensile test results indicated that welded and aged 0.070" thick 20% nickel sheet exhibits a sensitivity to heat-affected-zone embrittlement. This behavior, encountered in previous work on 0.072" sheet, was discussed in Section 1.2. Evidence obtained to date, suggests that the formation of the embrittled heat-affected zone is limited to relatively thin sheet. It should be noted that no sign of an embrittled zone was detected in bend tests made on 0.070" sheet welds in the as-welded condition.

Sound, ductile welds were produced in both the solution heat treated and cold worked 0.140" thick sheet using conventional TIG welding procedures. In this sheet thickness, weld heat affected zones were free of both defects and embrittlement, as determined by inspection and transverse tensile tests.

Welds made using various filler wires are compared on the basis of strength, toughness and ductility in Figure 187 and Table 111.

For welding solution heat treated sheet, the 18% nickel (250 KSI) and the 20% nickel, molybdenum containing wires, appear to offer the best balance of weld strength and toughness properties (Figure 187). Wherever maximum yield strength properties are desirable, the modified 20% nickel, molybdenum containing wire should definitely be considered (Figure 187). Weld fracture toughness values exhibited by this wire compared favorably with base material toughness (Table 111).

The relative performance of filler wires in welds in cold worked sheet did not parallel that observed in corresponding welds in solution heat treated material using the same heat treatment. This would be expected since the same maraging heat treatment was used for both material conditions (Figure 187). The test data indicated that the 18% nickel (300 KSI) filler wire is preferred on the basis of yield strength joint efficiency.

EFFECT OF SOLUTIONING TIME AND TEMPERATURE ON THE HARDNESS OF 20% NICKEL ALLOY

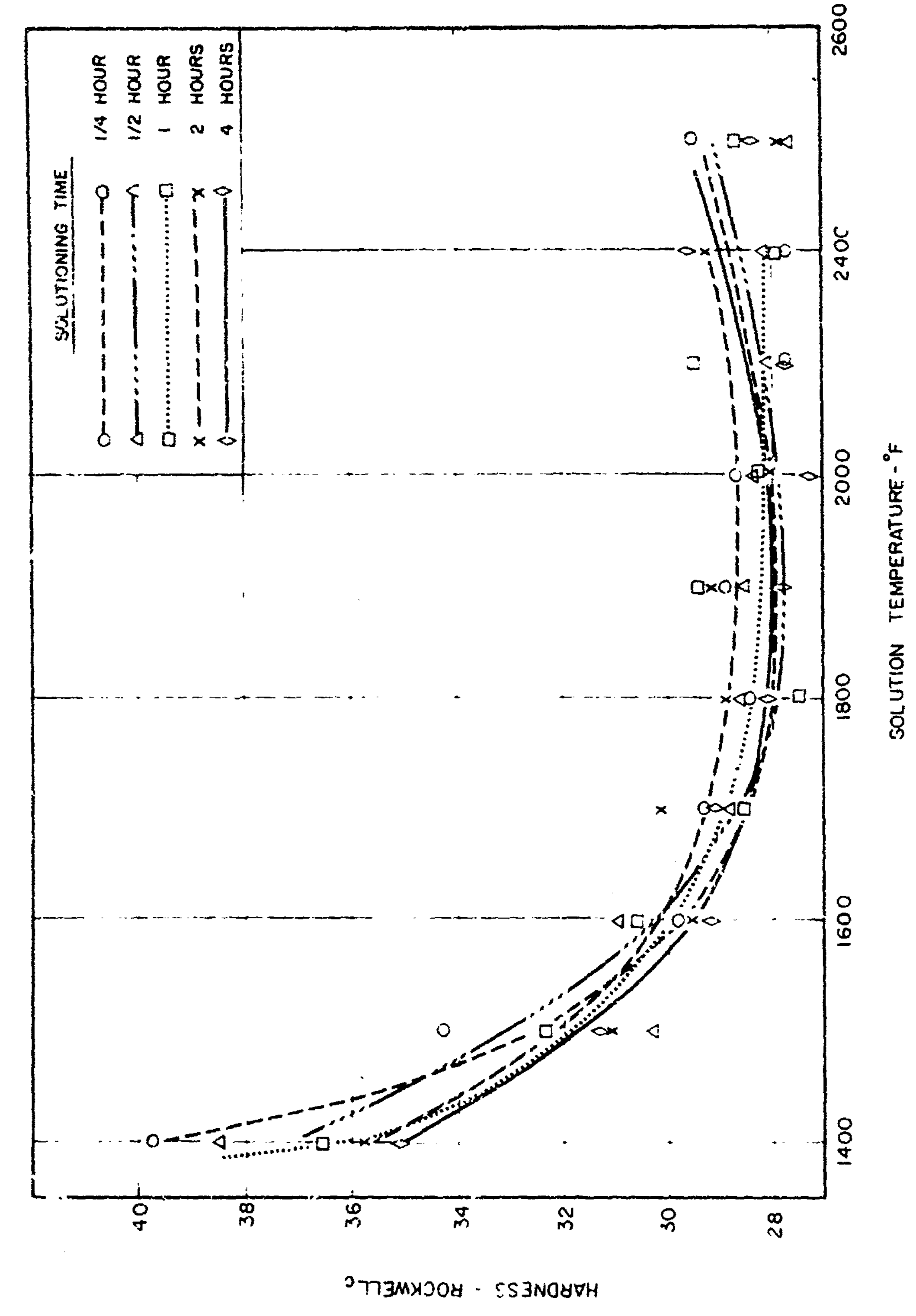


Figure 156

EFFECT OF MARAGING PARAMETERS ON THE HARDNESS OF SOLUTION TREATED 20% NICKEL ALLOY

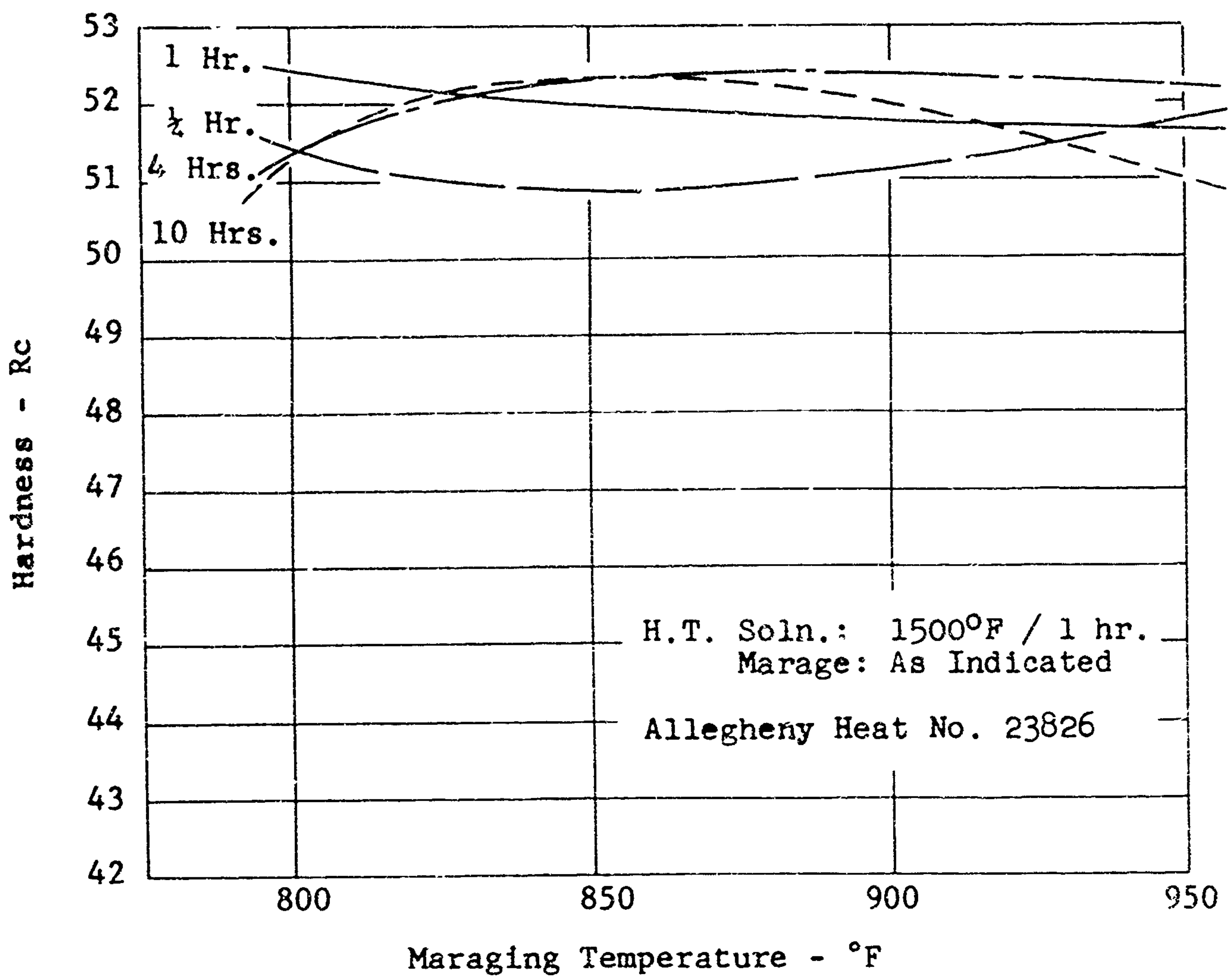


Figure 157

EFFECT OF SOLUTION TEMPERATURE ON THE LONGITUDINAL TENSILE PROPERTIES OF 20% NICKEL ALLOY

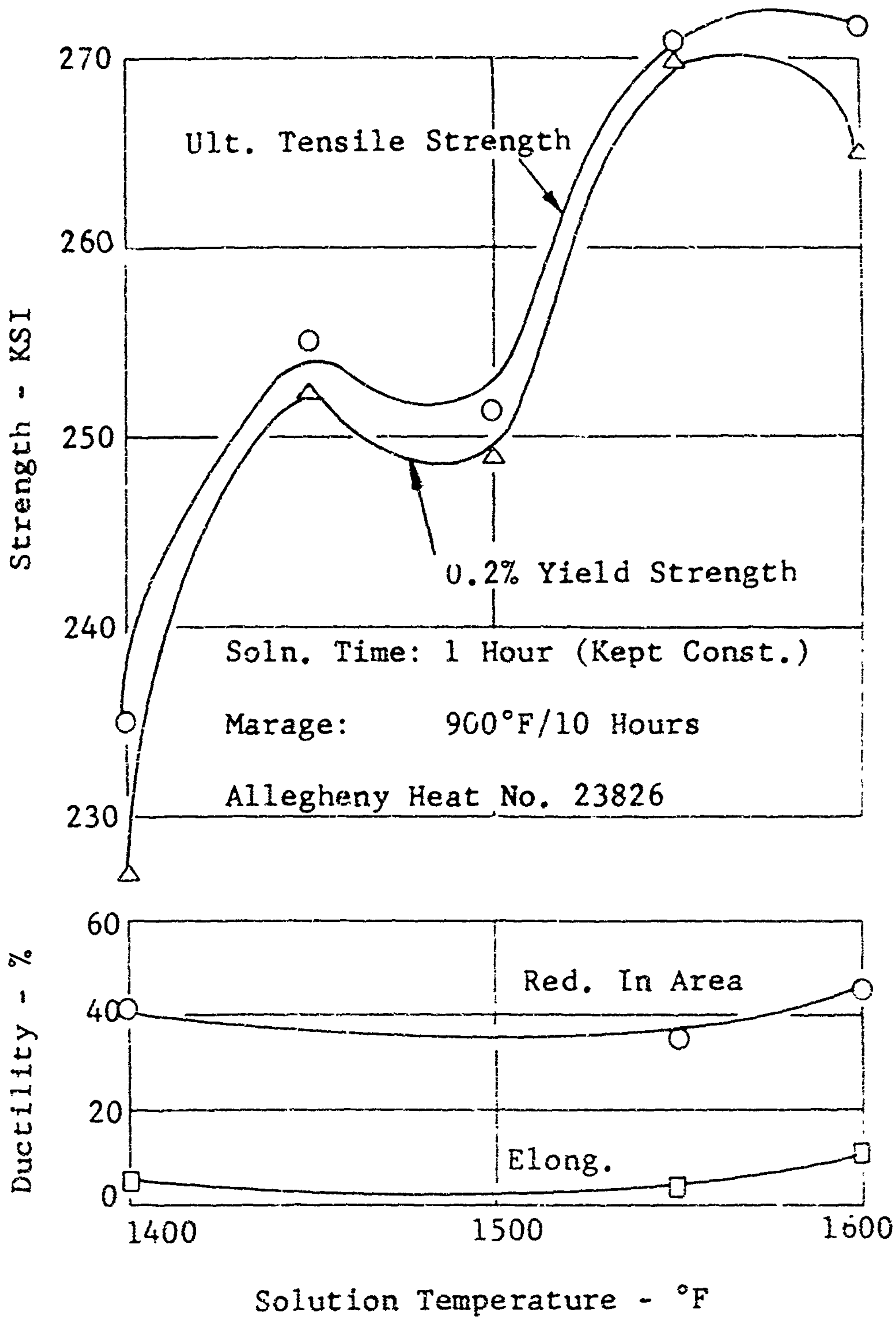


Figure 158

EFFECT OF SOLUTION TEMPERATURE ON THE TRANSVERSE
TENSILE PROPERTIES OF 20% NICKEL ALLOY

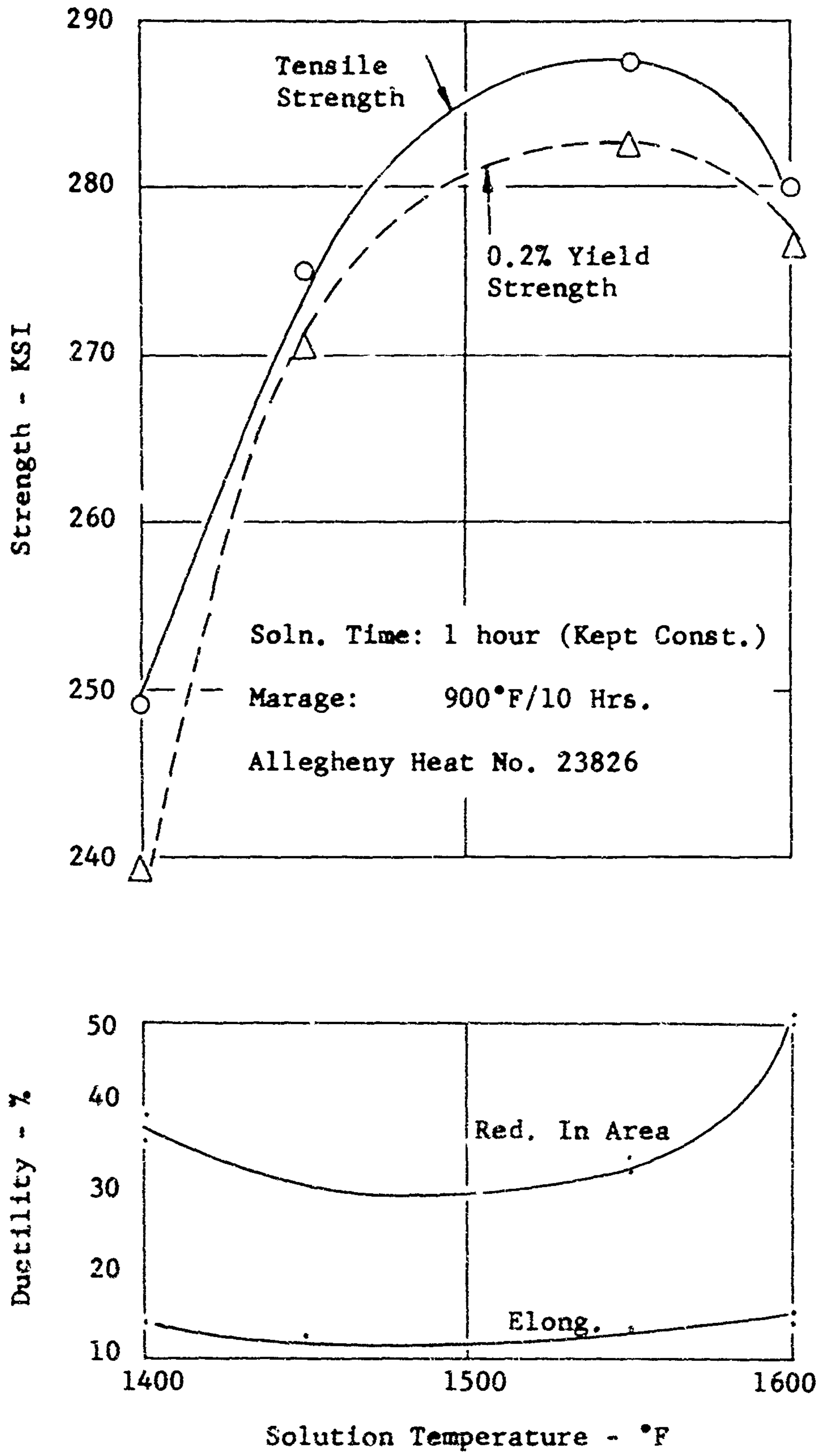


Figure 159

EFFECT OF SOLUTION TREATMENT ON THE FRACTURE TOUGHNESS OF 20% NICKEL ALLOY

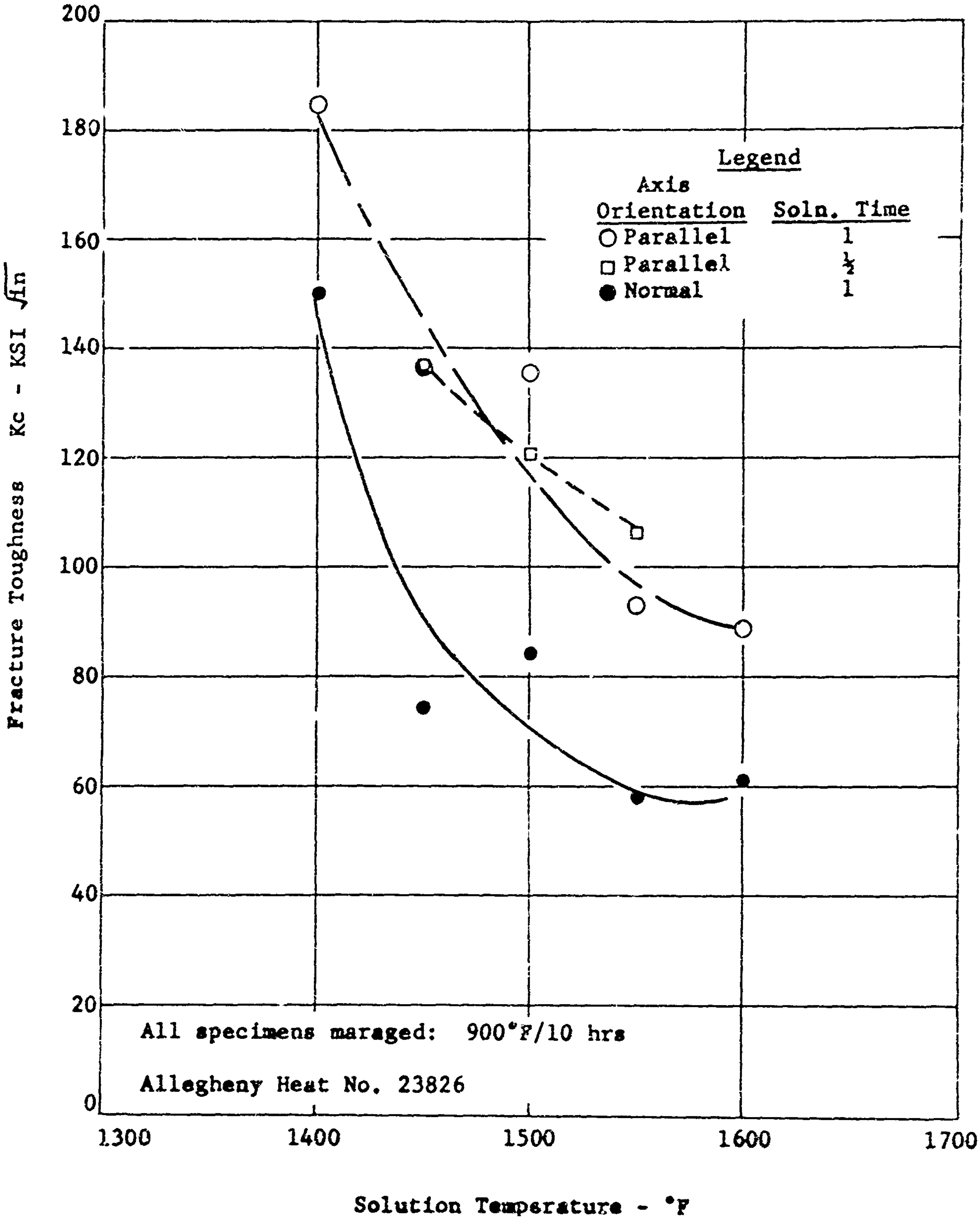


Figure 160

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON
THE LONGITUDINAL YIELD STRENGTH OF
20% NICKEL ALLOY

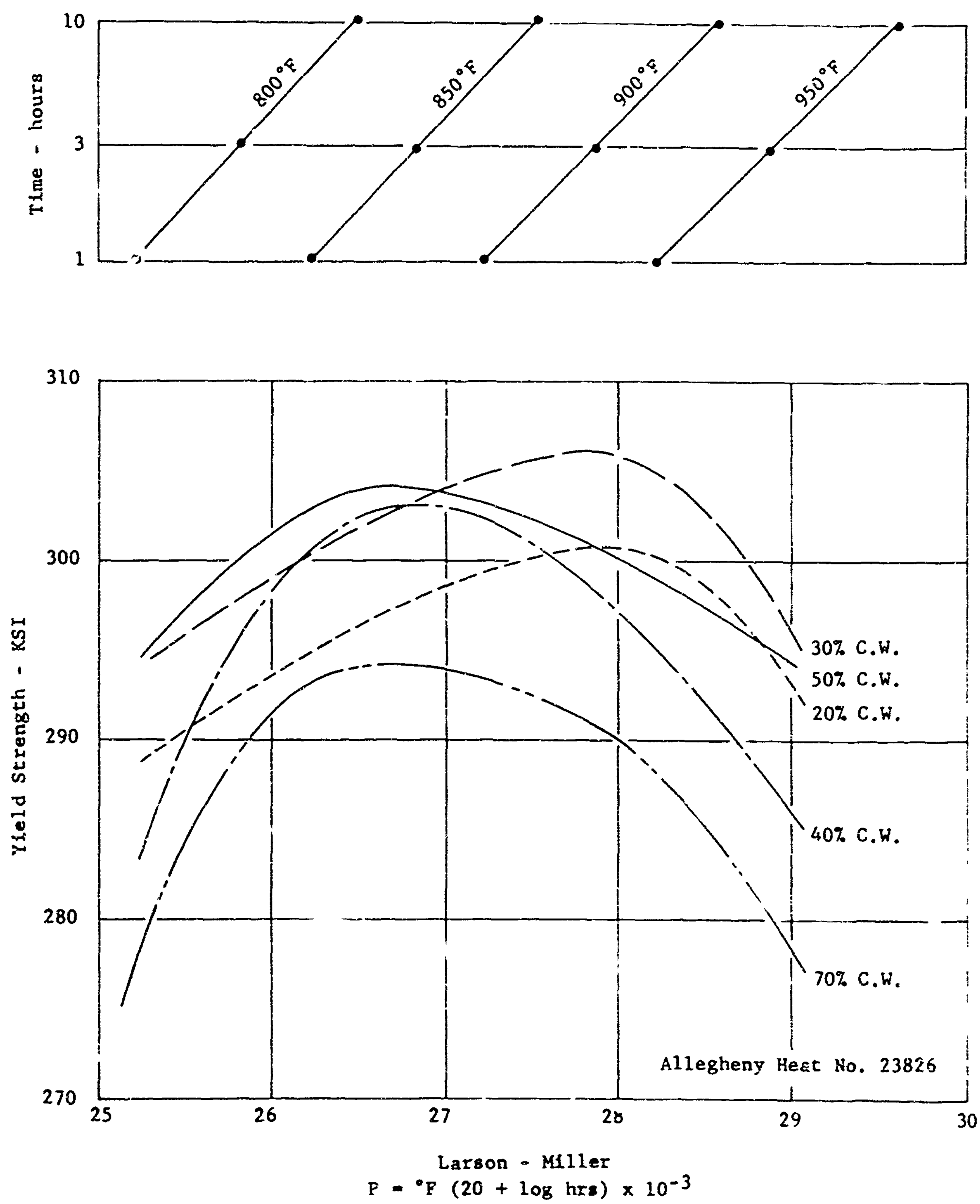


Figure 161

OPTIMIZATION OF LONGITUDINAL YIELD STRENGTH RESPONSE
OF COLD WORKED 20% NICKEL ALLOY

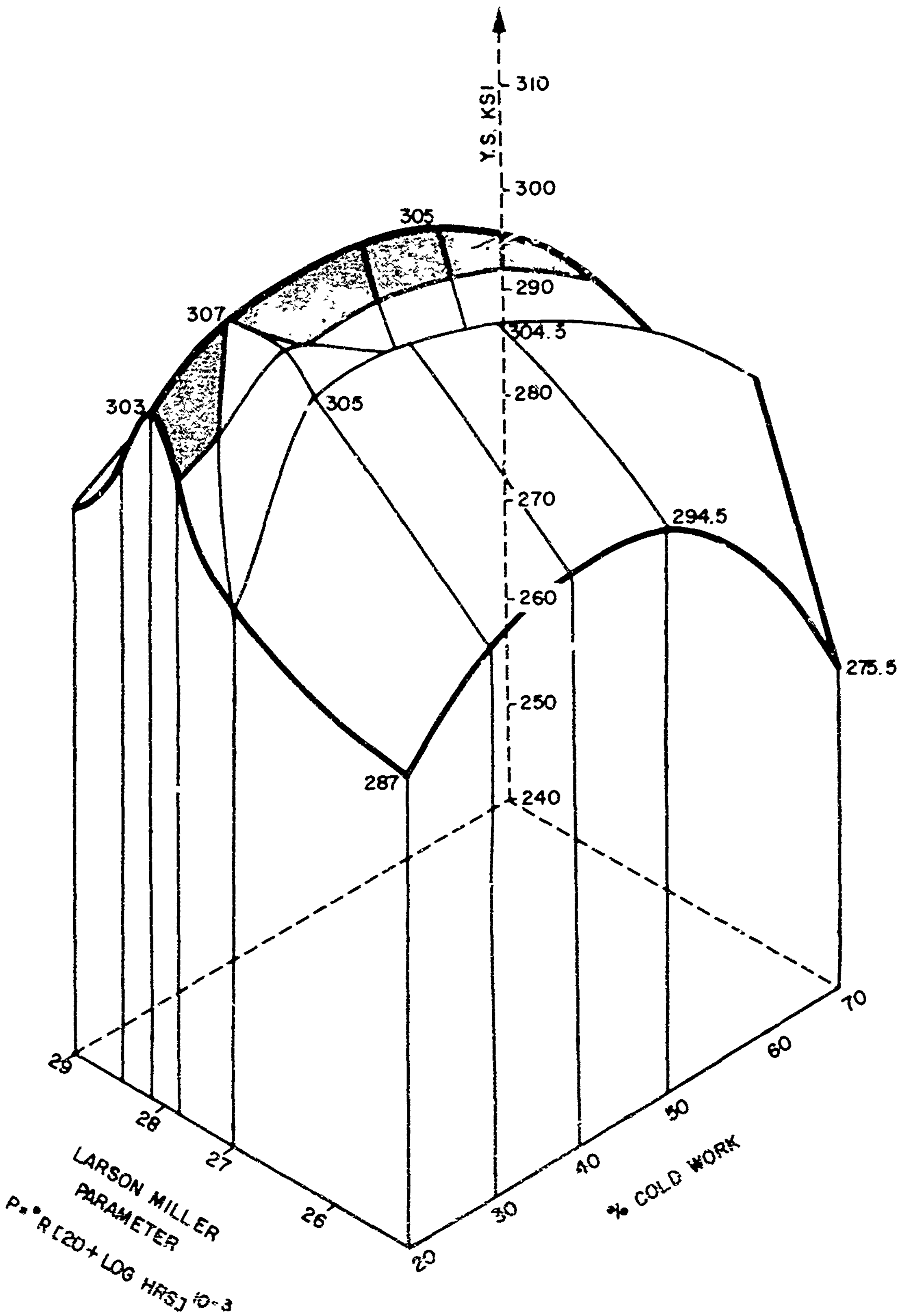


Figure 162

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON THE FRACTURE TOUGHNESS OF 20% NI ALLOY*

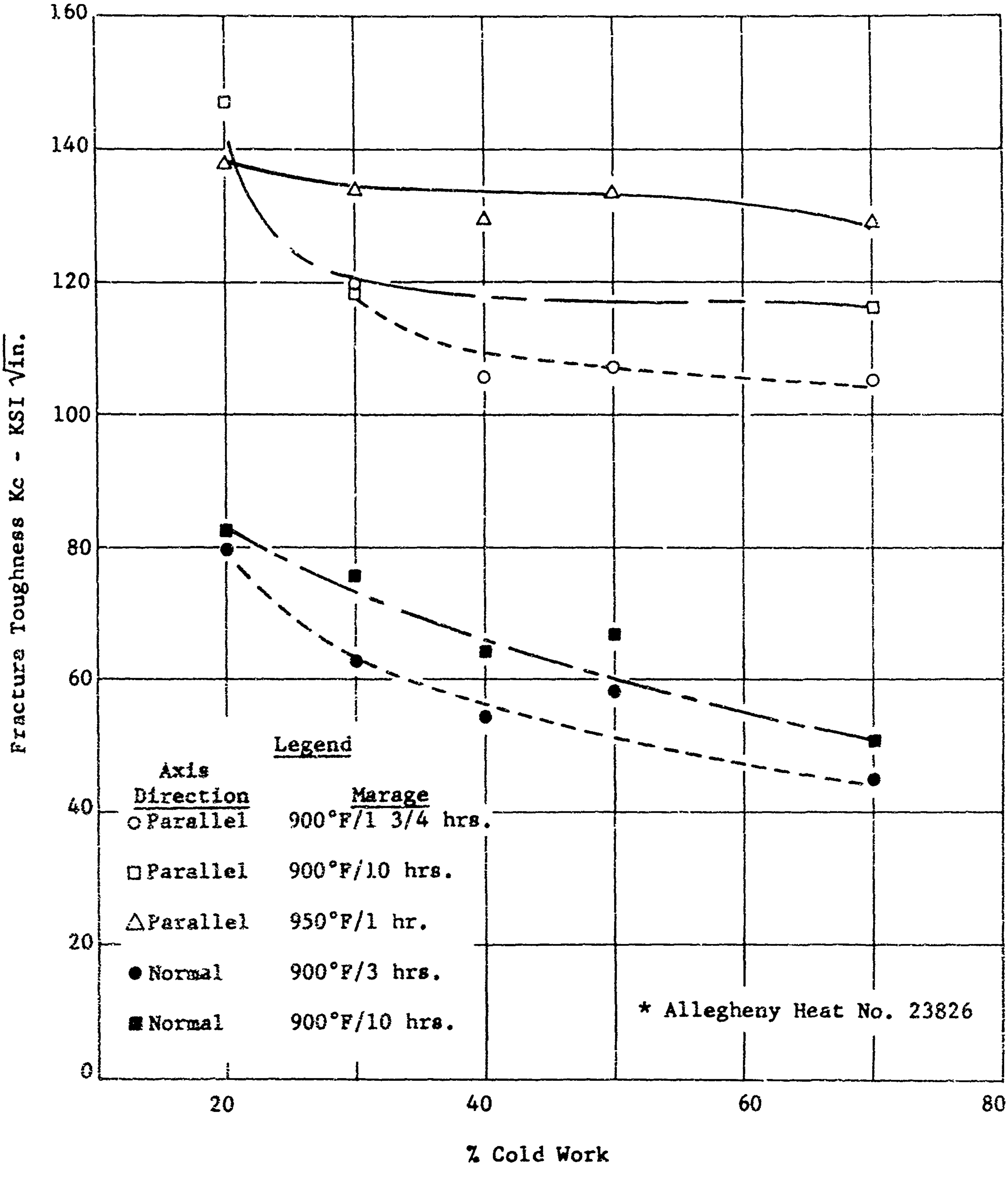


Figure 163

EFFECT OF MARAGING PARAMETERS (REPRESENTED BY LARSON-MILLER PARAMETER) ON THE LONGITUDINAL YIELD STRENGTH OF WARM WORKED 20% NICKEL ALLOY

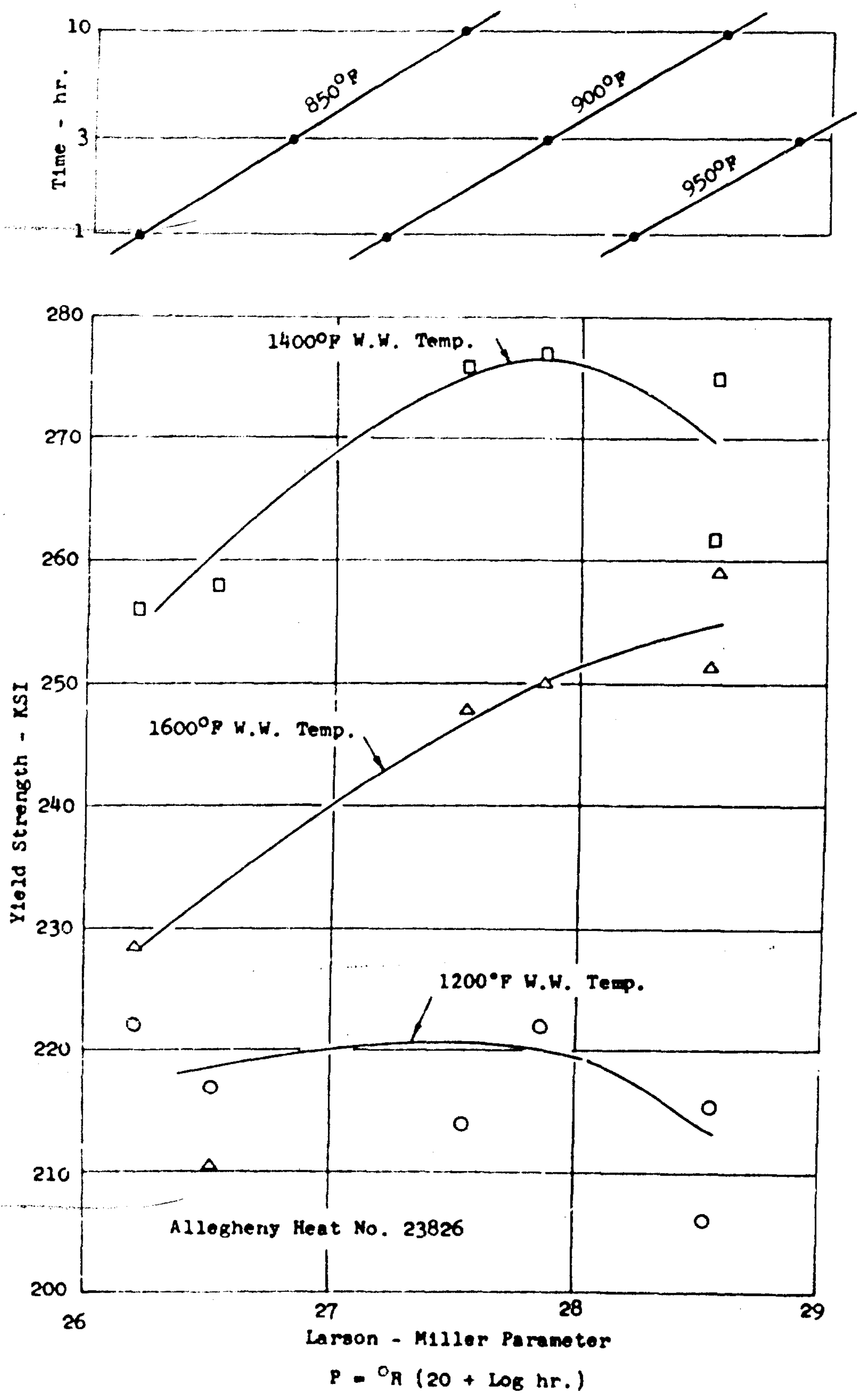


Figure 164

EFFECT OF MARAGING PARAMETERS
(AS REPRESENTED BY LARSON - MILLER)
ON THE TRANSVERSE YIELD STRENGTH OF
WARM WORKED 20% NICKEL ALLOY

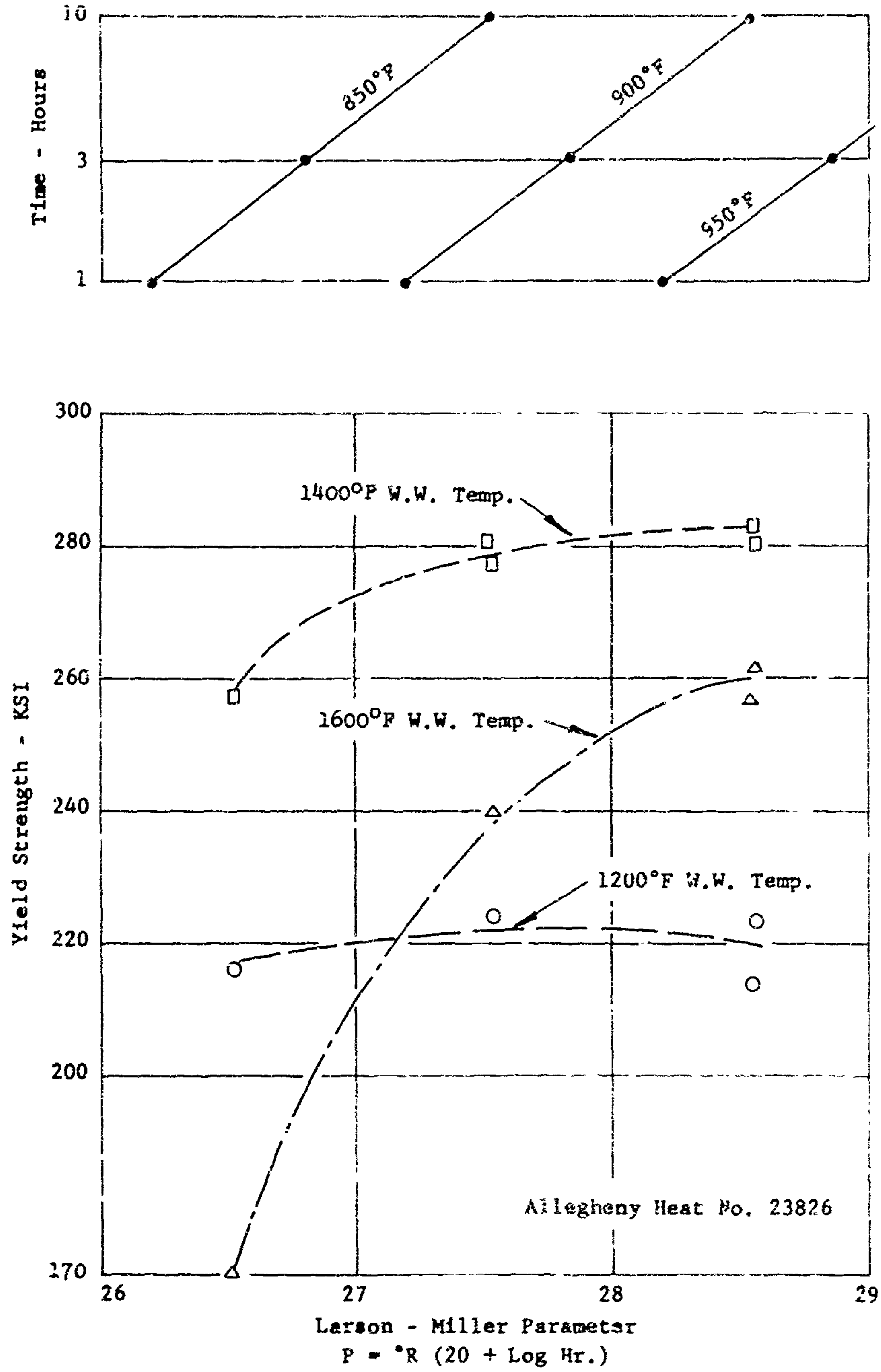


Figure 165

OPTIMIZATION OF LONGITUDINAL YIELD STRENGTH RESPONSE OF WARM WORKED 20% NICKEL ALLOY

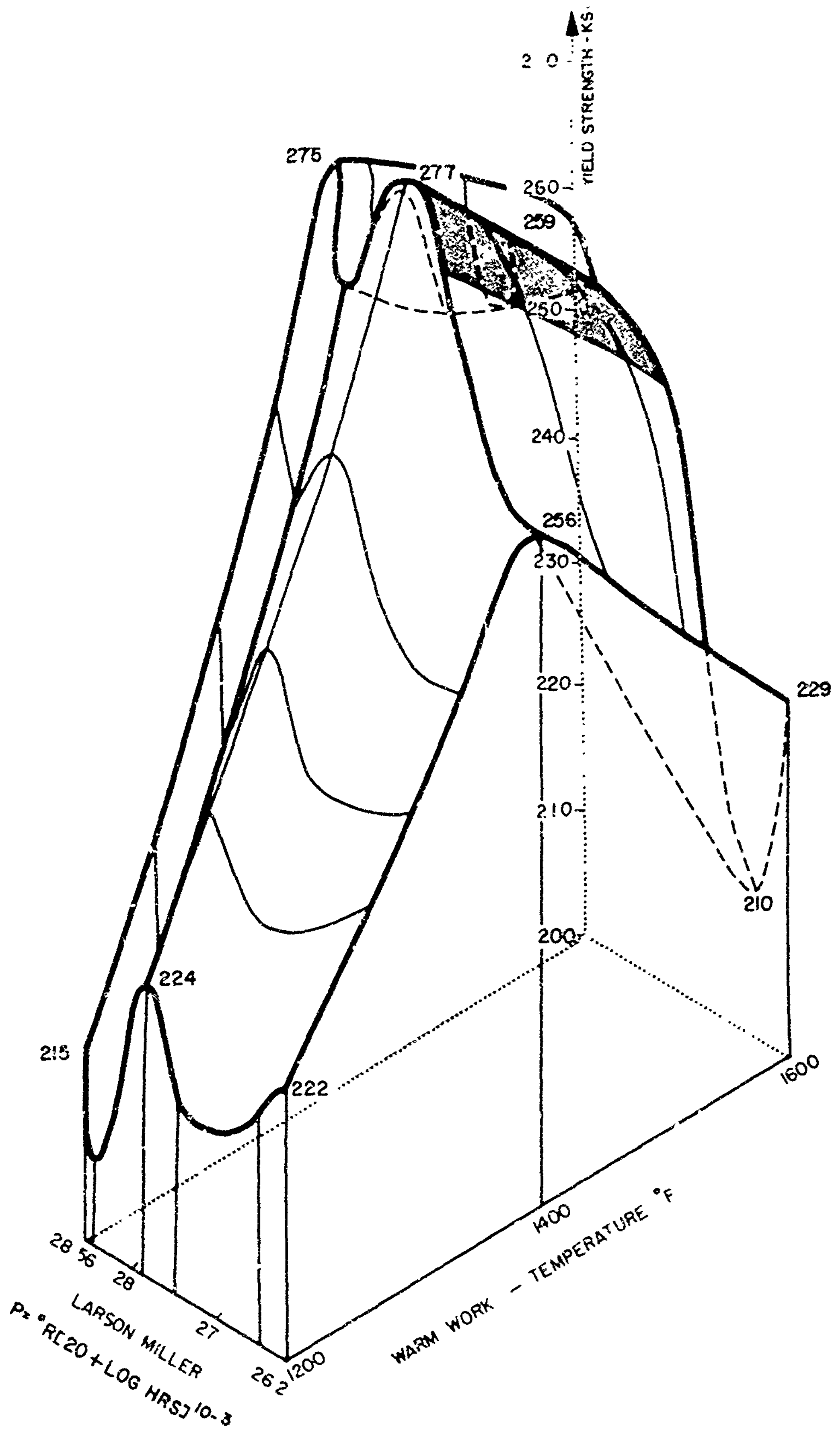


Figure 166

EFFECT OF WARM WORKING TEMPERATURE
ON THE FRACTURE TOUGHNESS OF 20% Ni ALLOY

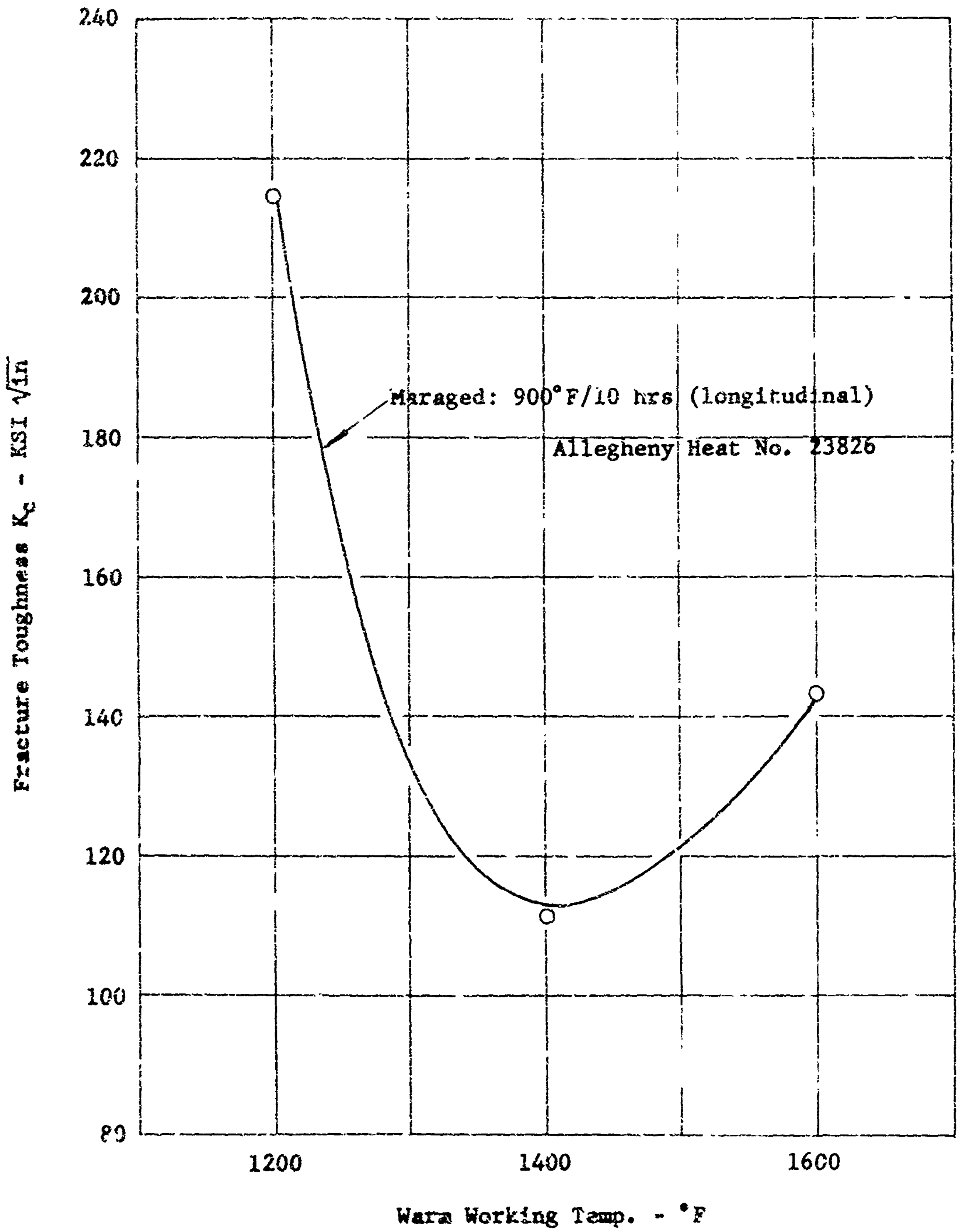


Figure 167

3914

ELEVATED TEMPERATURE TENSILE PROPERTIES OF
SOLUTION ANNEALED 20% NICKEL ALLOY

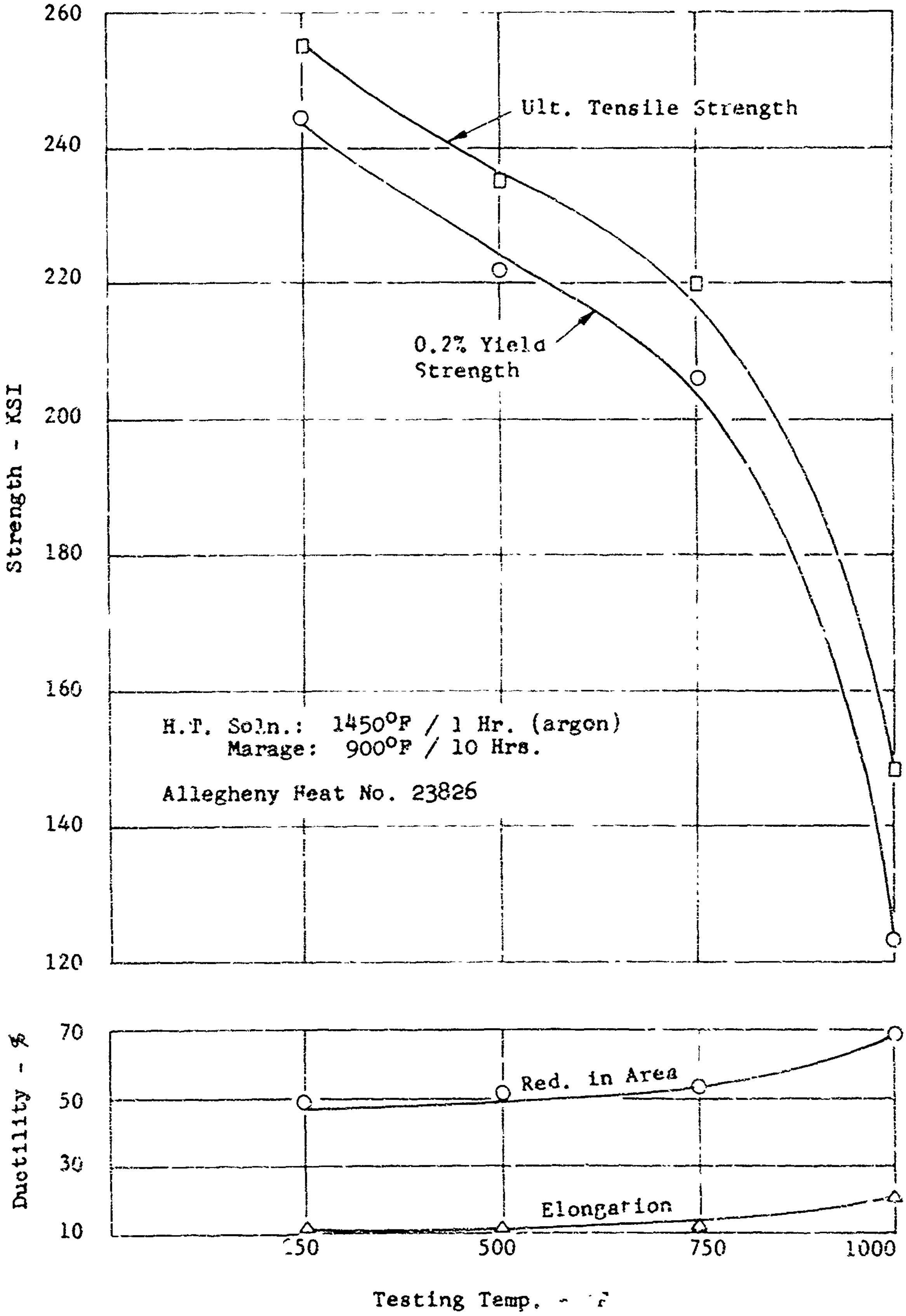


Figure 168

HEAT TREAT RESPONSE OF A THICK SECTION (20% NICKEL ALLO)

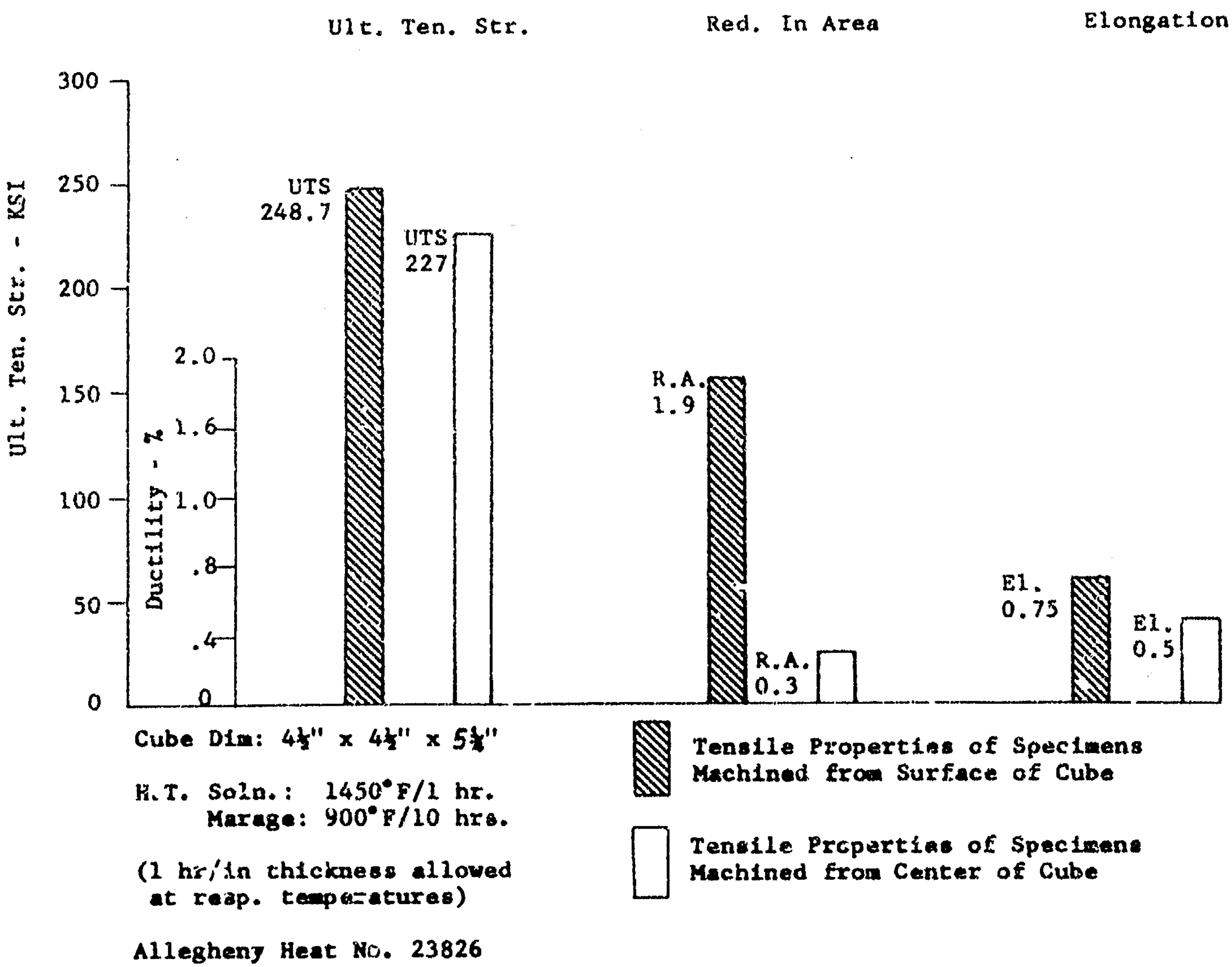


Figure 169

EFFECT OF FORGING REDUCTION ON THE PROPERTIES

20% NICKEL ALLOY

LOCATION: VERTICAL CENTER

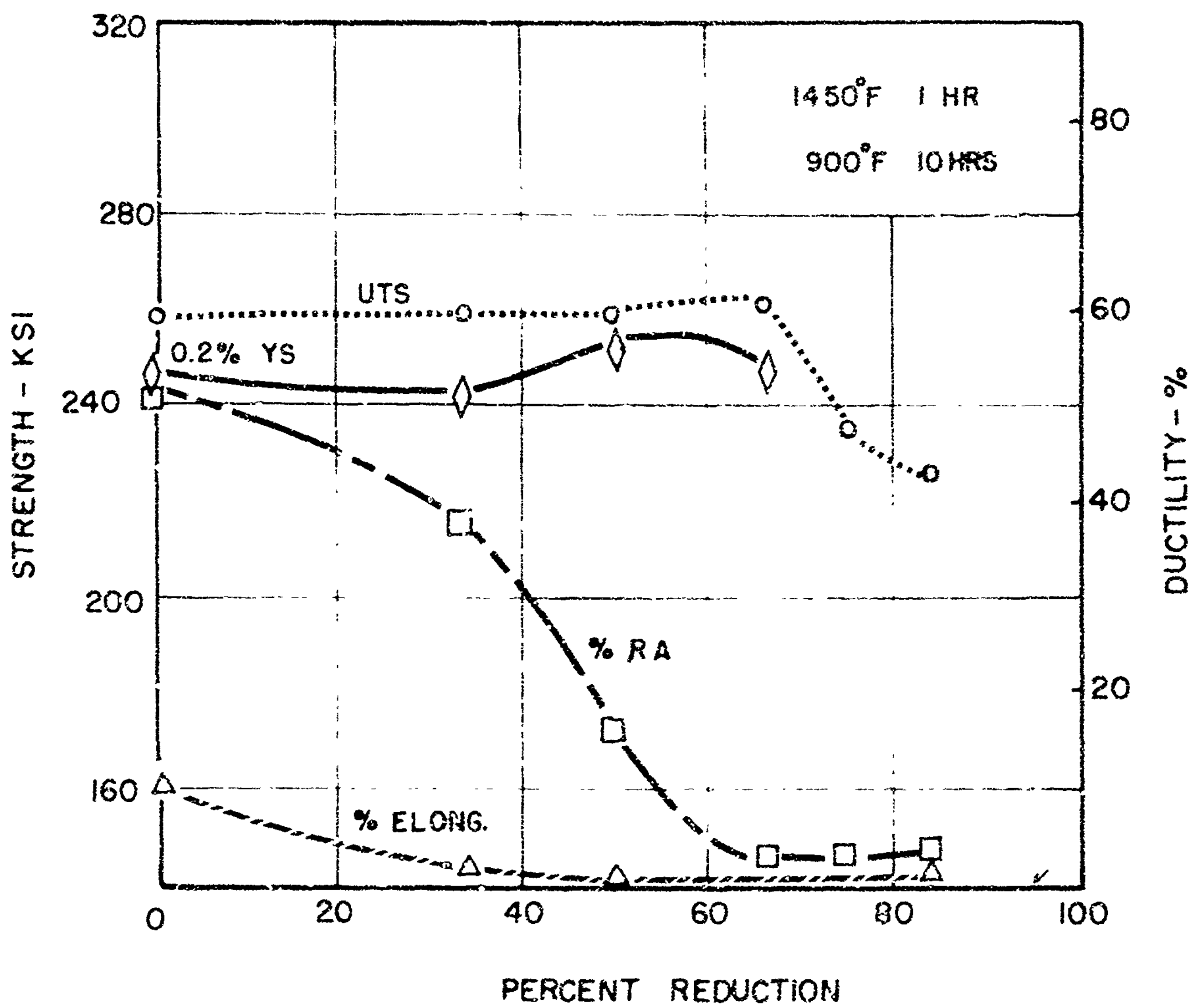


Figure 170

EFFECT OF FORGING REDUCTION ON THE PROPERTIES

20% NICKEL ALLOY

LOCATION: VERTICAL-EDGE

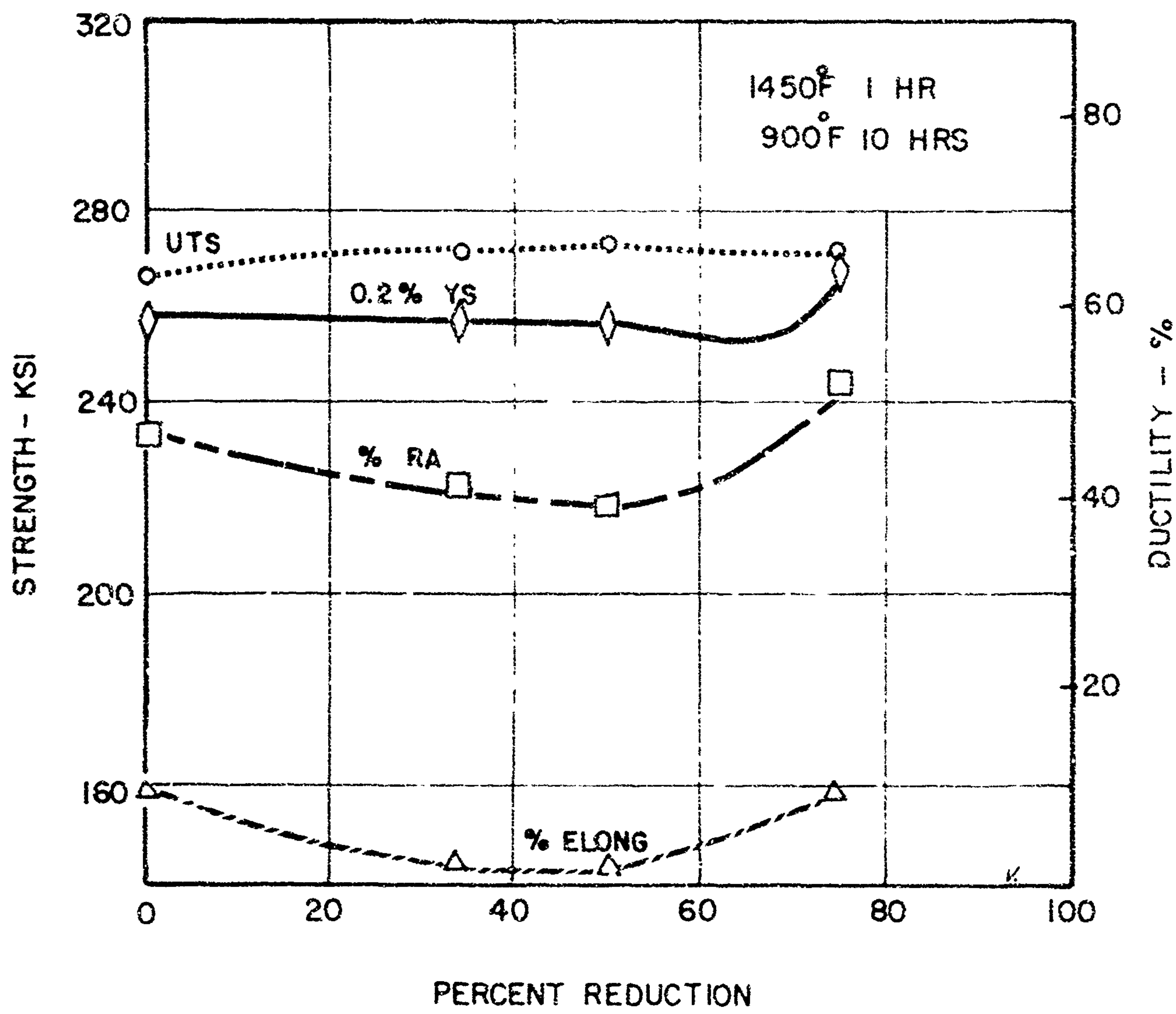


Figure 171

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 20% NICKEL ALLOY

LOCATION: HORIZONTAL CENTER

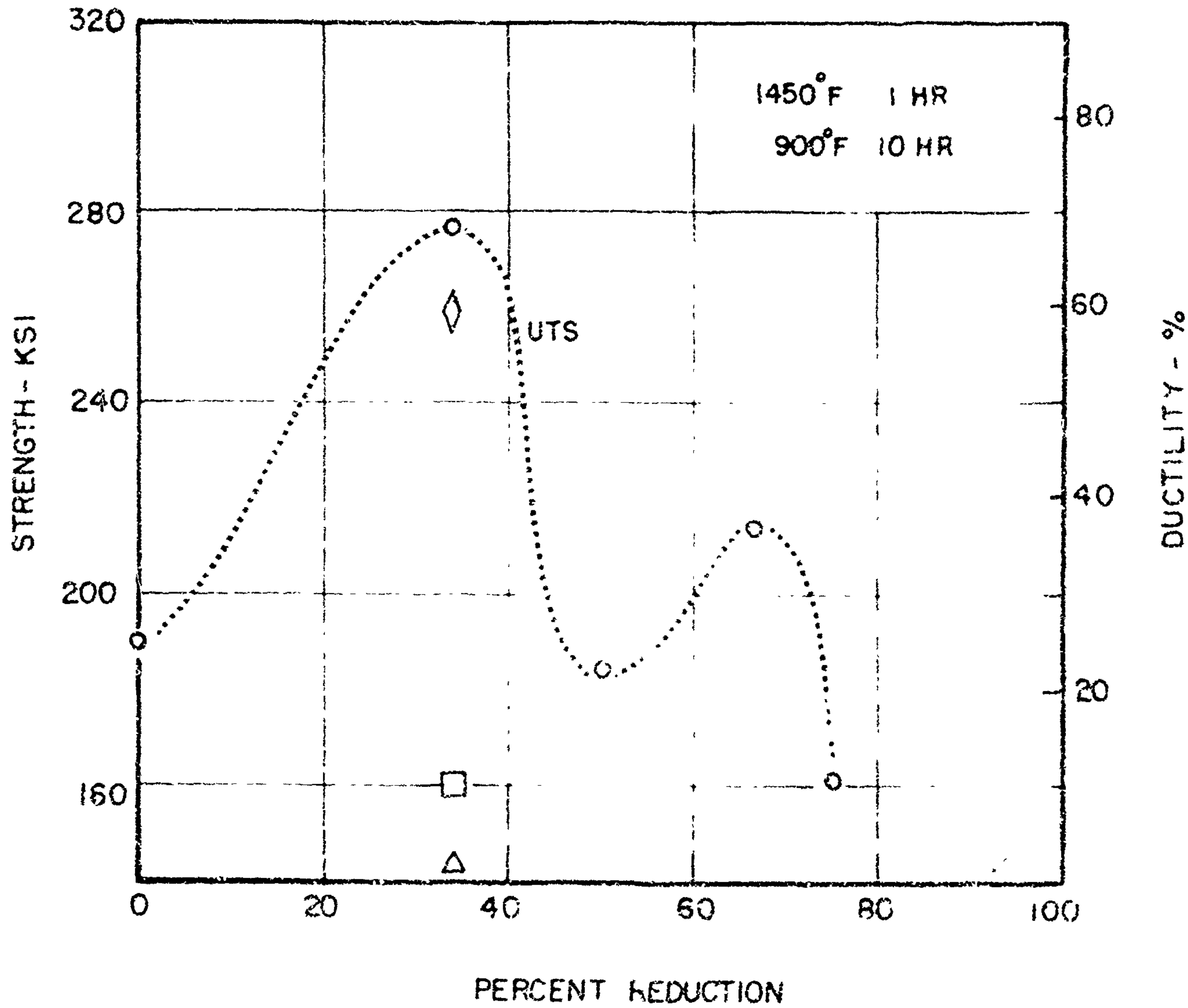


Figure 172

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 20% NICKEL ALLOY

LOCATION: HORIZONTAL EDGE

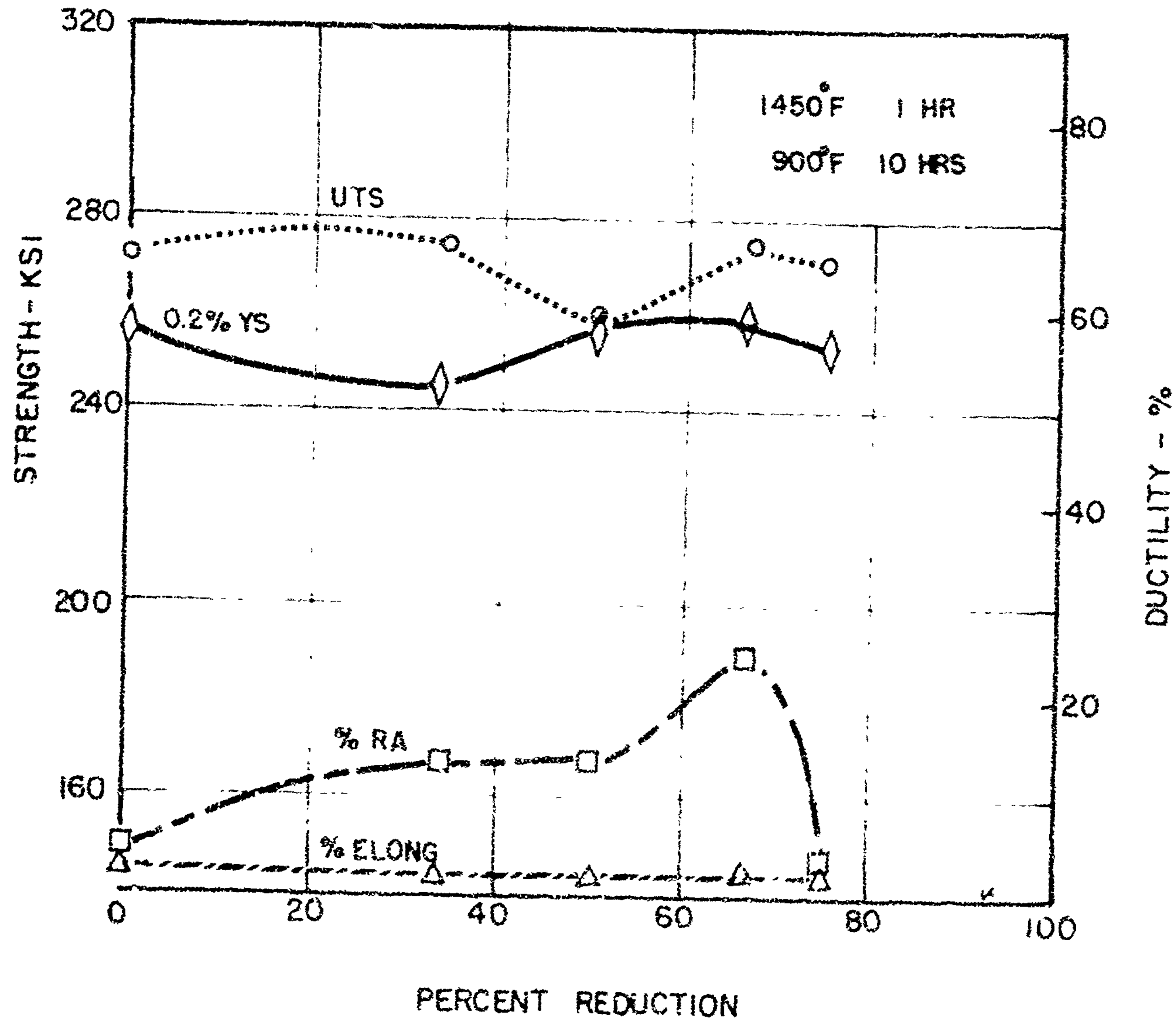


Figure 173

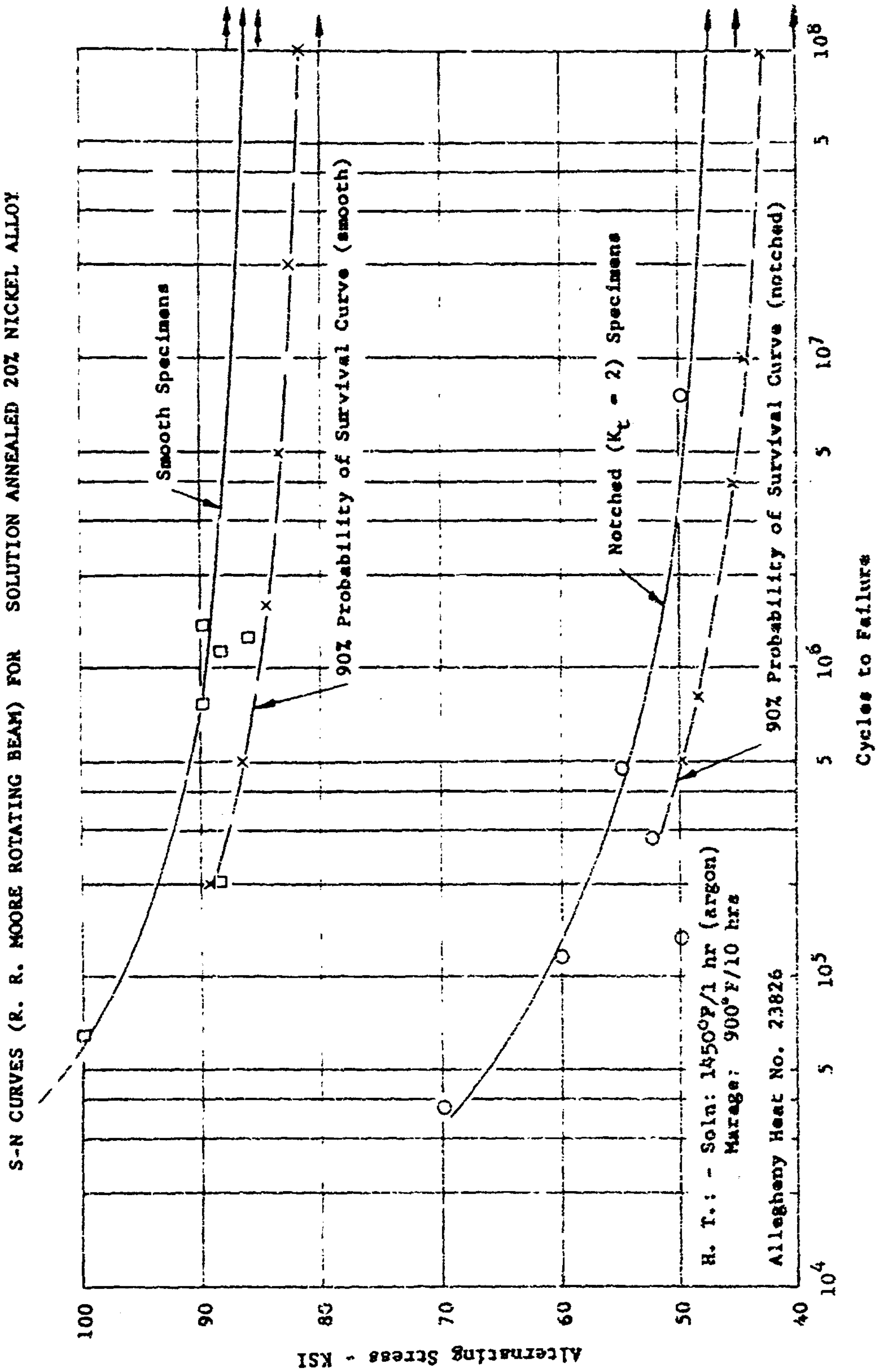

S-N CURVES (R. R. MOORE ROTATING BEAM) FOR SOLUTION ANNEALED 20% NICKEL ALLOY
Smooth Specimens
90% Probability of Survival Curve (smooth)
Notched (K_t = 2) Specimens
90% Probability of Survival Curve (notched)
H. T.: - Soln: 1450°F/1 hr (argon)
Marage: 900°F/10 hrs
Allegheny Heat No. 23826
Alternating Stress - KSI
Cycles to Failure
100
90
80
70
60
50
40
10^4
5
10^5
5
10^6
5
10^7
5
10^8

Figure 174

S-N CURVE (R. R. MOORE ROTATING BEAM) FOR 30% COLD WORKED 20% Ni ALLOY

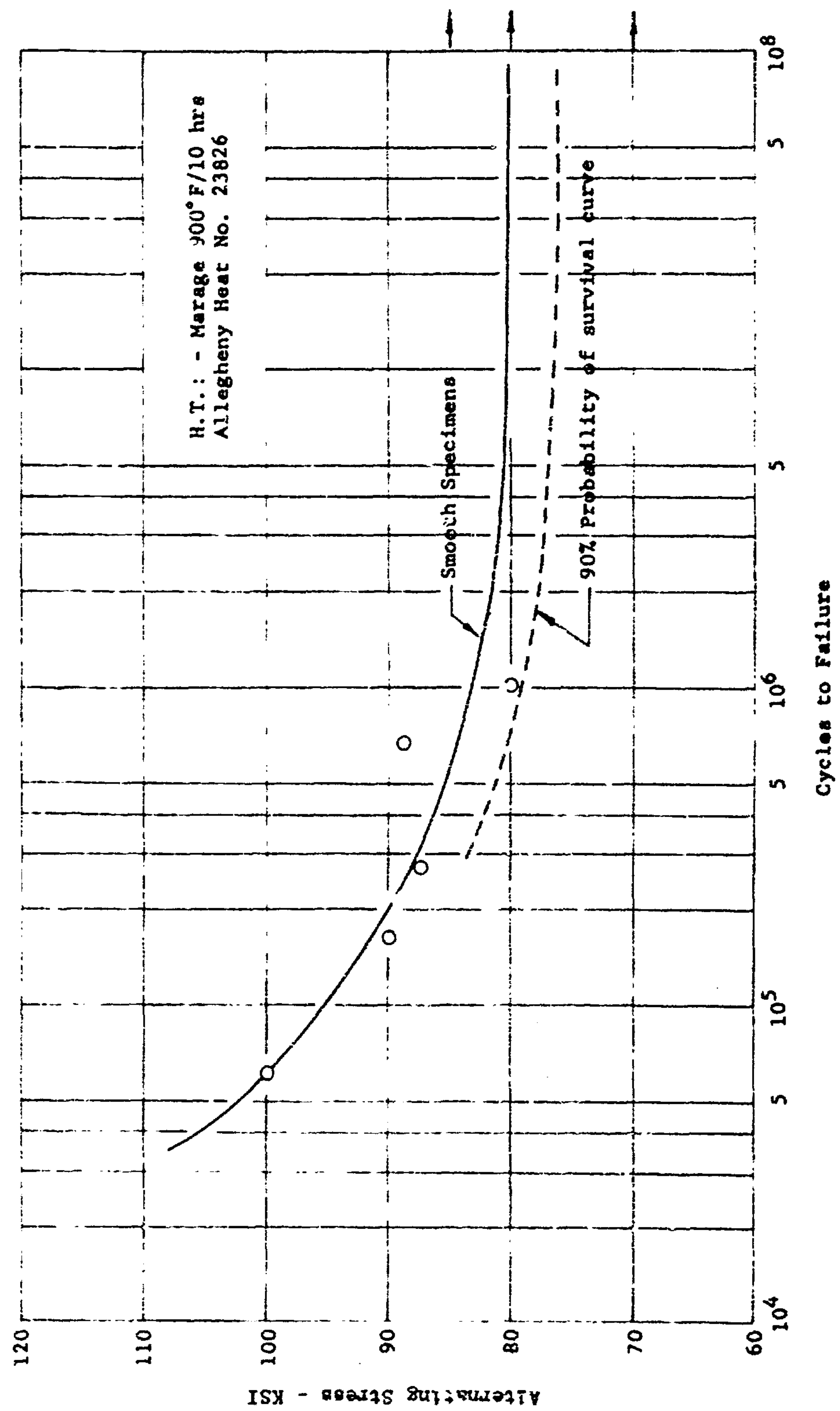


Figure 175

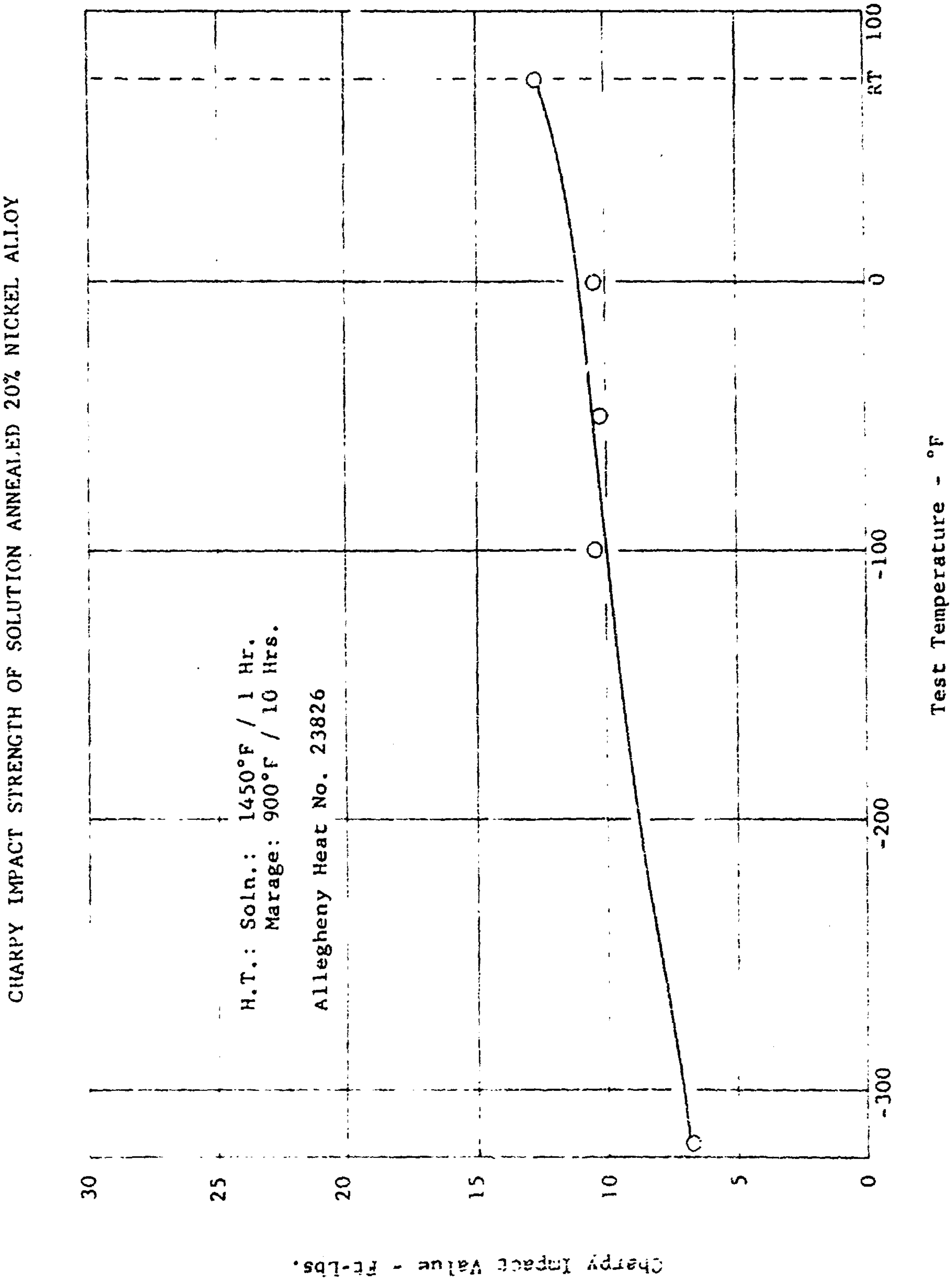

CHARPY IMPACT STRENGTH OF SOLUTION ANNEALED 20% NICKEL ALLOY
H.T.: Soln.: 1450°F / 1 Hr.
Marage: 900°F / 10 Hrs.
Allegheny Heat No. 23826
Charpy Impact Value - Ft-Lbs.
Test Temperature - °F
30
25
20
15
10
5
0
-300
-200
-100
0
RT
100

Figure 176

CHARPY IMPACT STRENGTH OF COLD WORKED 20% NICKEL ALLOY

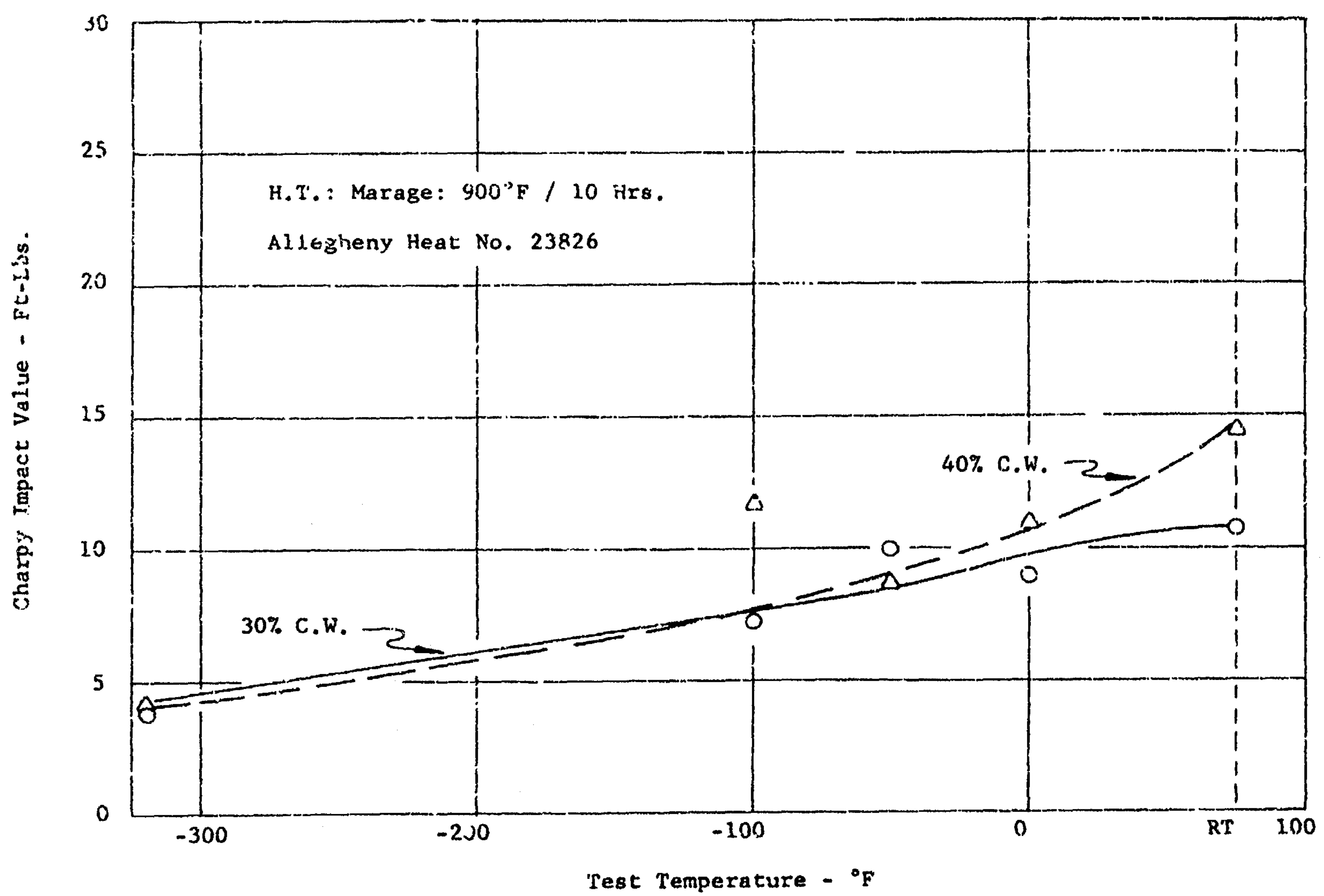


Figure 177

COMPARISON OF FRACTURE TOUGHNESS OF 20% NICKEL ALLOY IN COLD WORKED AND ANNEALED CONDITIONS

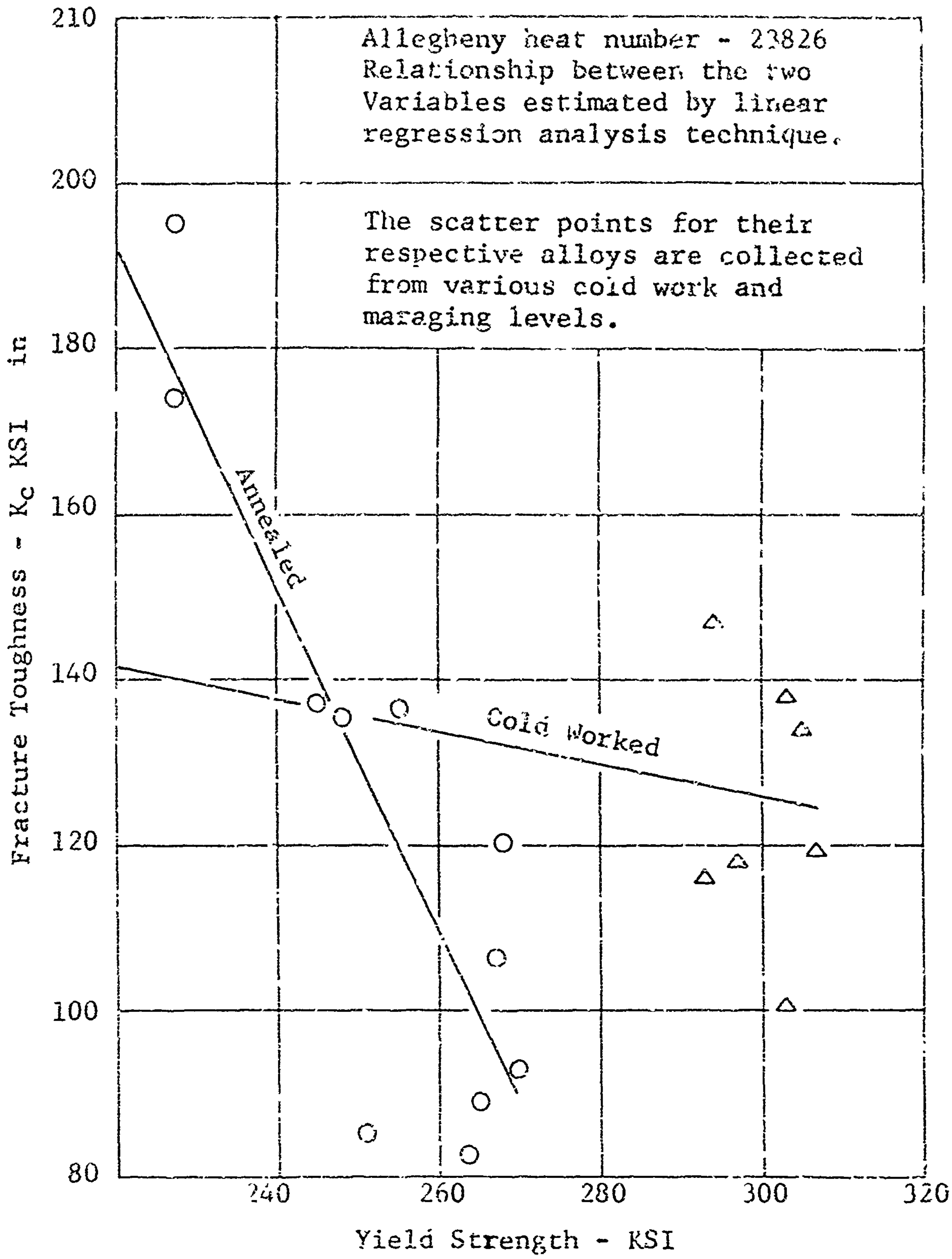
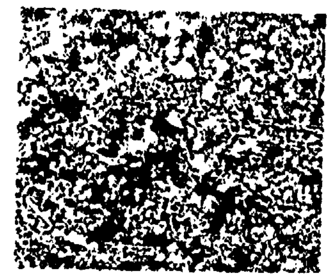


Figure 178

MICROSTRUCTURE OF SOLUTION TREATED AND SOLUTION TREATED AND MARAGED 20% NICKEL ALLOY

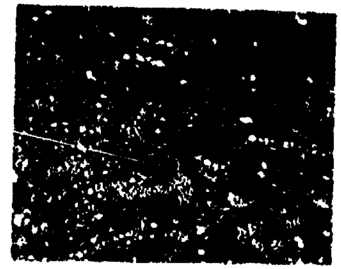
Solutioned 1500°F/1 hr.



Mag. 500 X

Etchant: Marble's + Modified Fry's

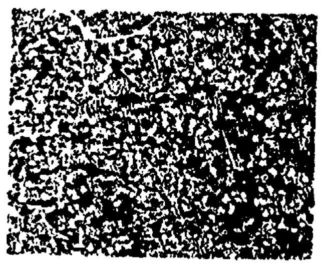
Solutioned 1500°F/1 hr.



Mag. 18000 X

Two Stage Carbon Replica

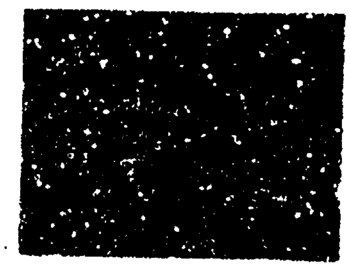
Solutioned 1500°F/1 hr., Maraged 900°F/10 hrs.



Mag. 500 X

Etchant: Marble's + Modified Fry's

Solutioned 1500°F/1 hr., Maraged 900°F/10 hrs.



Mag. 18000 X

Two Stage Carbon Replica

Figure 179

20% NICKEL ALLOY WELD HARDNESS DATA
VERTICAL TRAVERSE ALONG WELD CENTERLINE

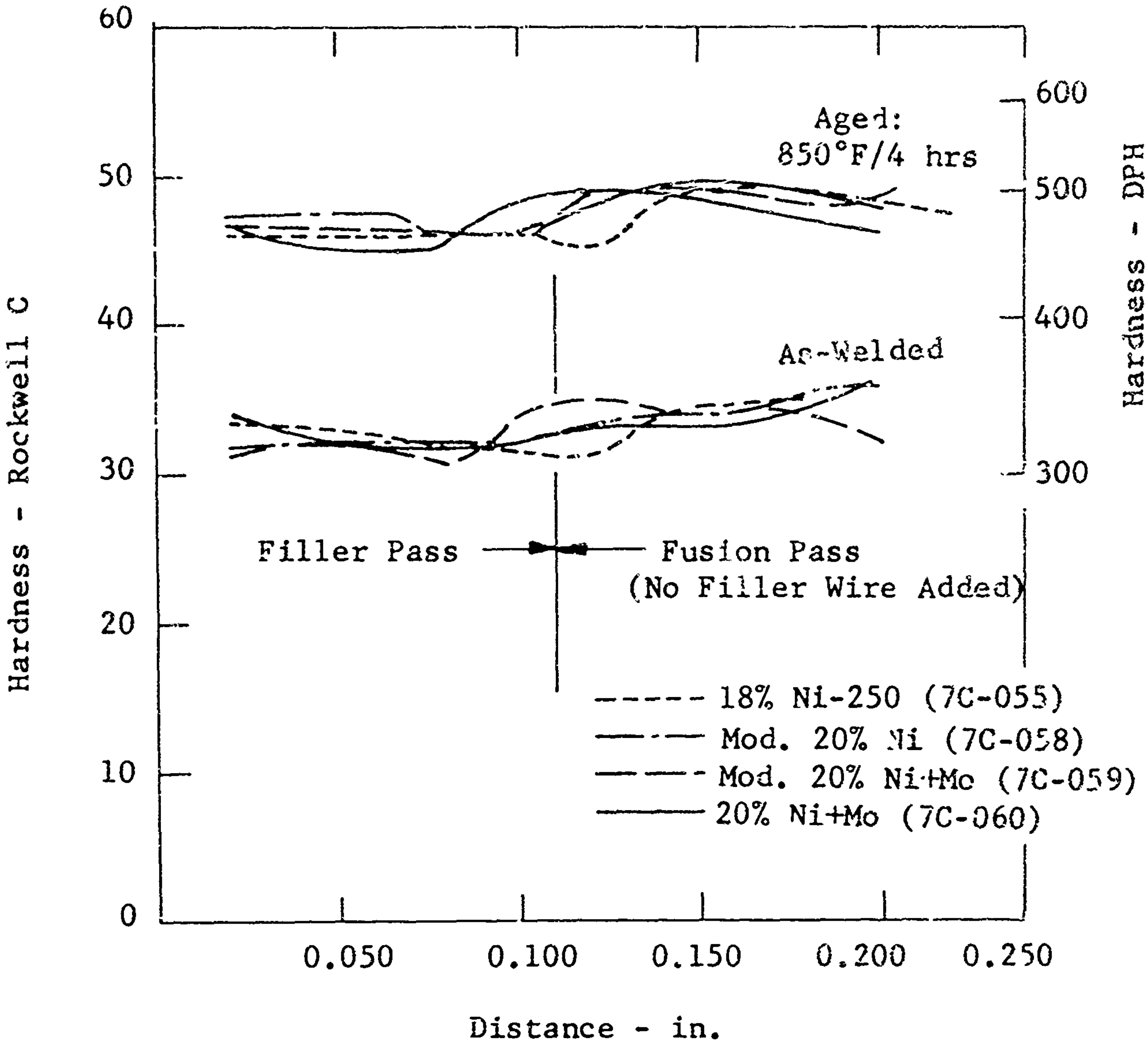


Figure 180

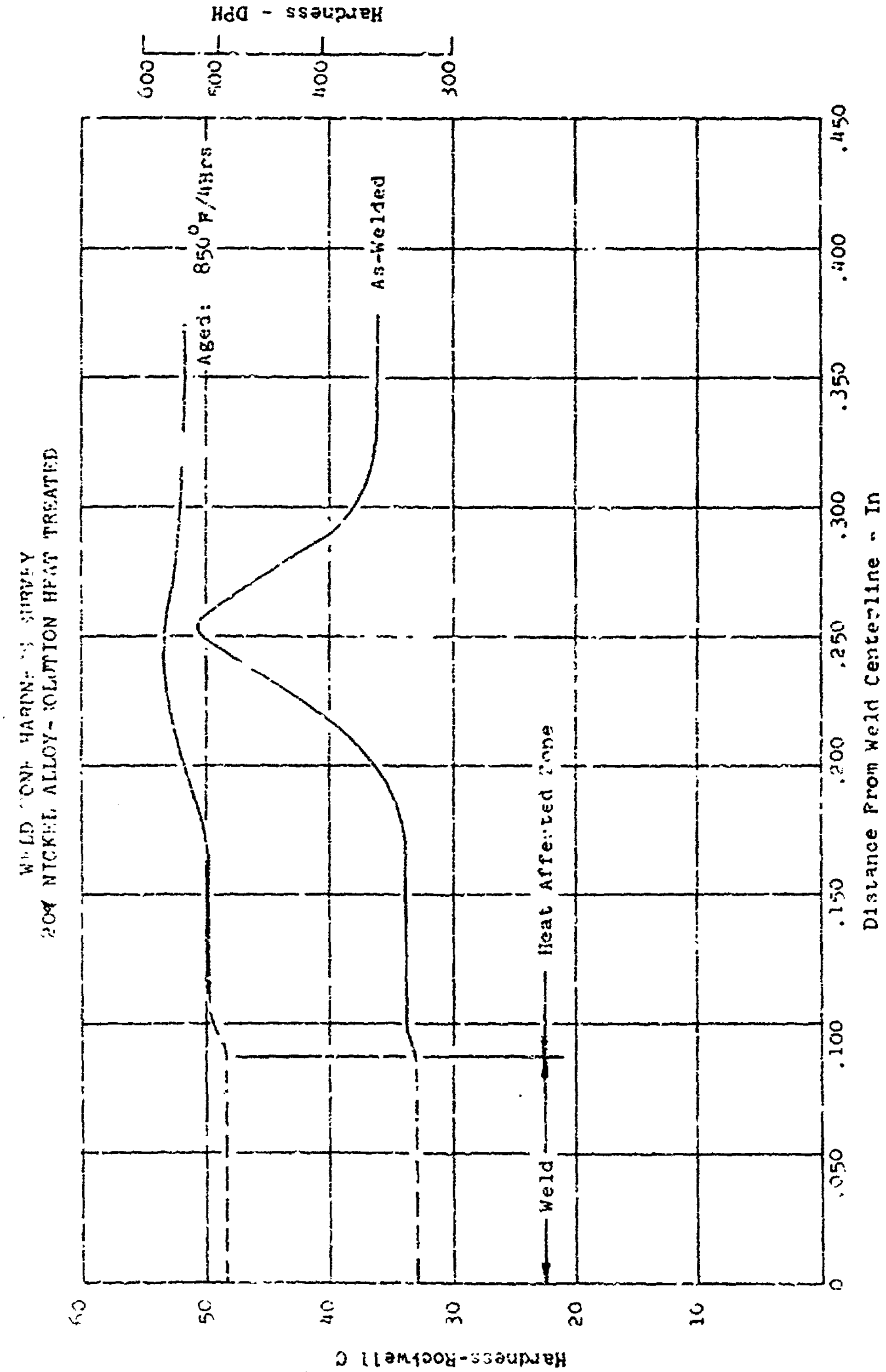

20% NICKEL ALLOY- SOLUTION HEAT TREATED
Hardness - DPH
600
500
400
300
Aged: 850°F/4Hrs
As-Welded
Weld
Heat Affected Zone
Hardness-Rockwell C
60
50
40
30
20
10
0
.050
.100
.150
.200
.250
.300
.350
.400
.450
Distance From Weld Centerline - In

Figure 131

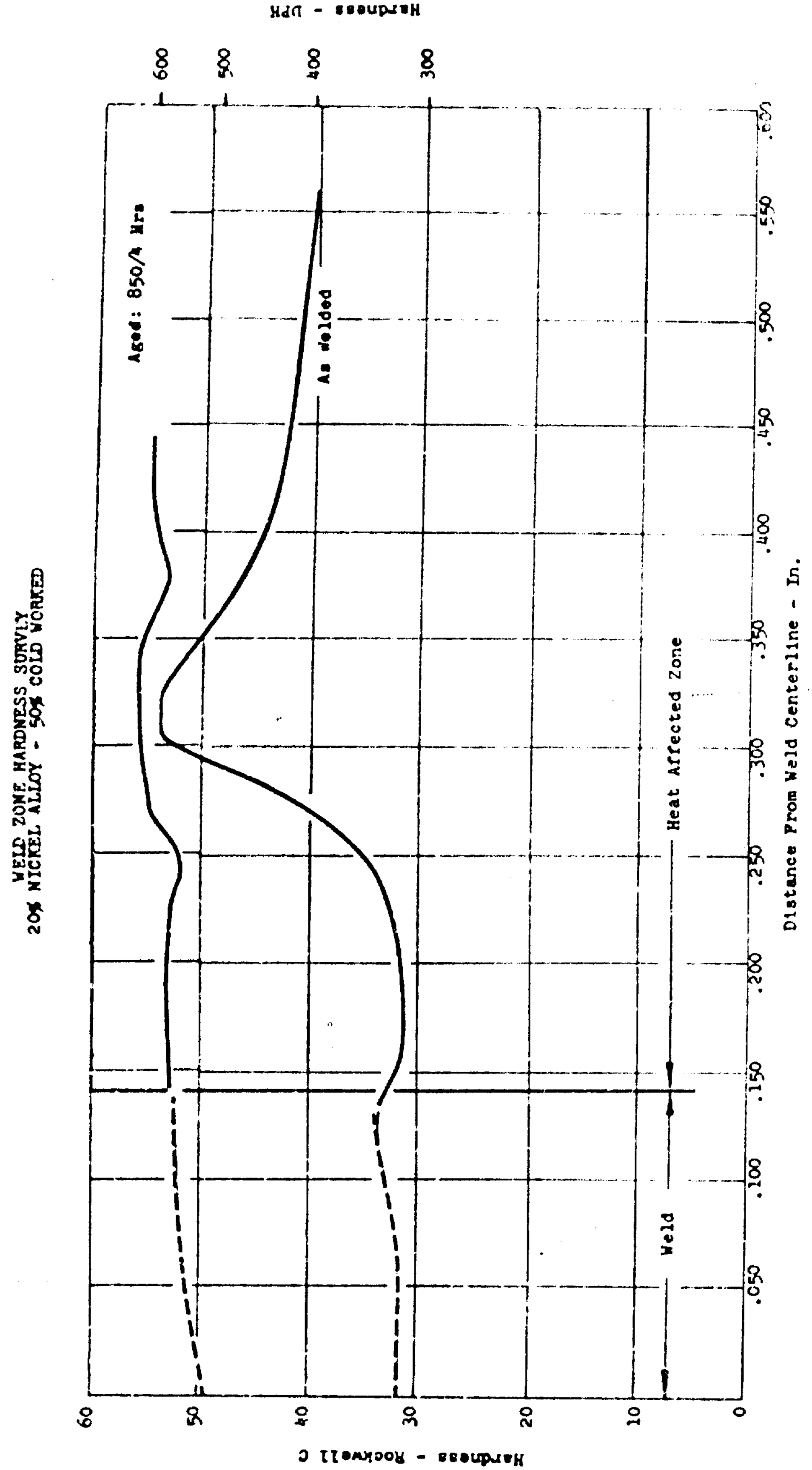
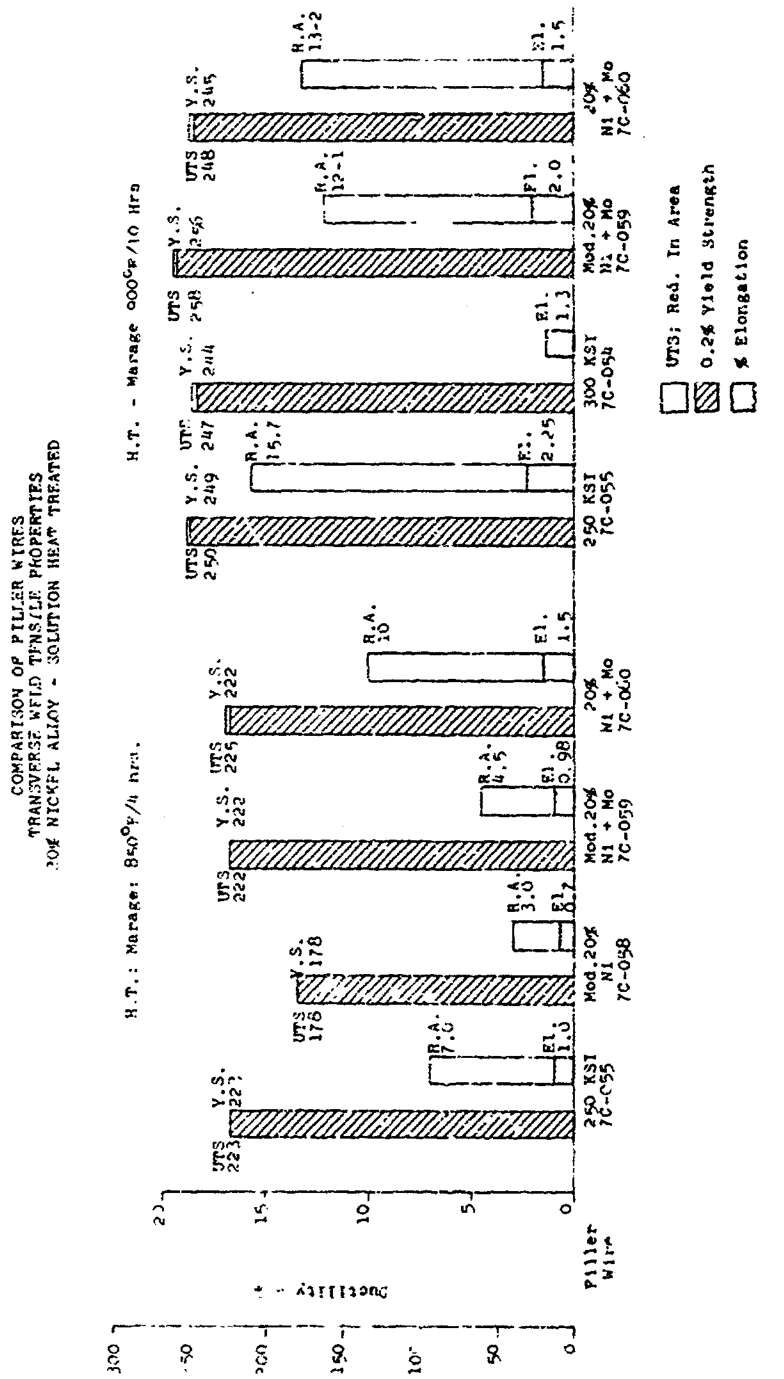

WELD ZONE HARDNESS SURVLY
20% NICKEL ALLOY - 50% COLD WORKED
Aged: 850/4 Hrs
As Welded
Heat Affected Zone
Weld
Distance From Weld Centerline - In.
Hardness - Rockwell C
Hardness - DPH
600
500
400
300
60
50
40
30
20
10
0
.050
.100
.150
.200
.250
.300
.350
.400
.450
.500
.550

Figure 182



COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE PROPERTIES
20% NICKEL ALLOY - SOLUTION HEAT TREATED
H.T.: Marage: 850°F/4 hrs.
H.T. - Marage 900°F/10 Hrs
Strength - KSI
Ductility - %
Filler Wire
250 KSI 7C-055
Mod.20% Ni 7C-058
Mod.20% Ni + Mo 7C-059
20% Ni + Mo 7C-060
300 KSI 7C-054
UTS; Red. In Area
0.2% Yield Strength
% Elongation

Figure 183

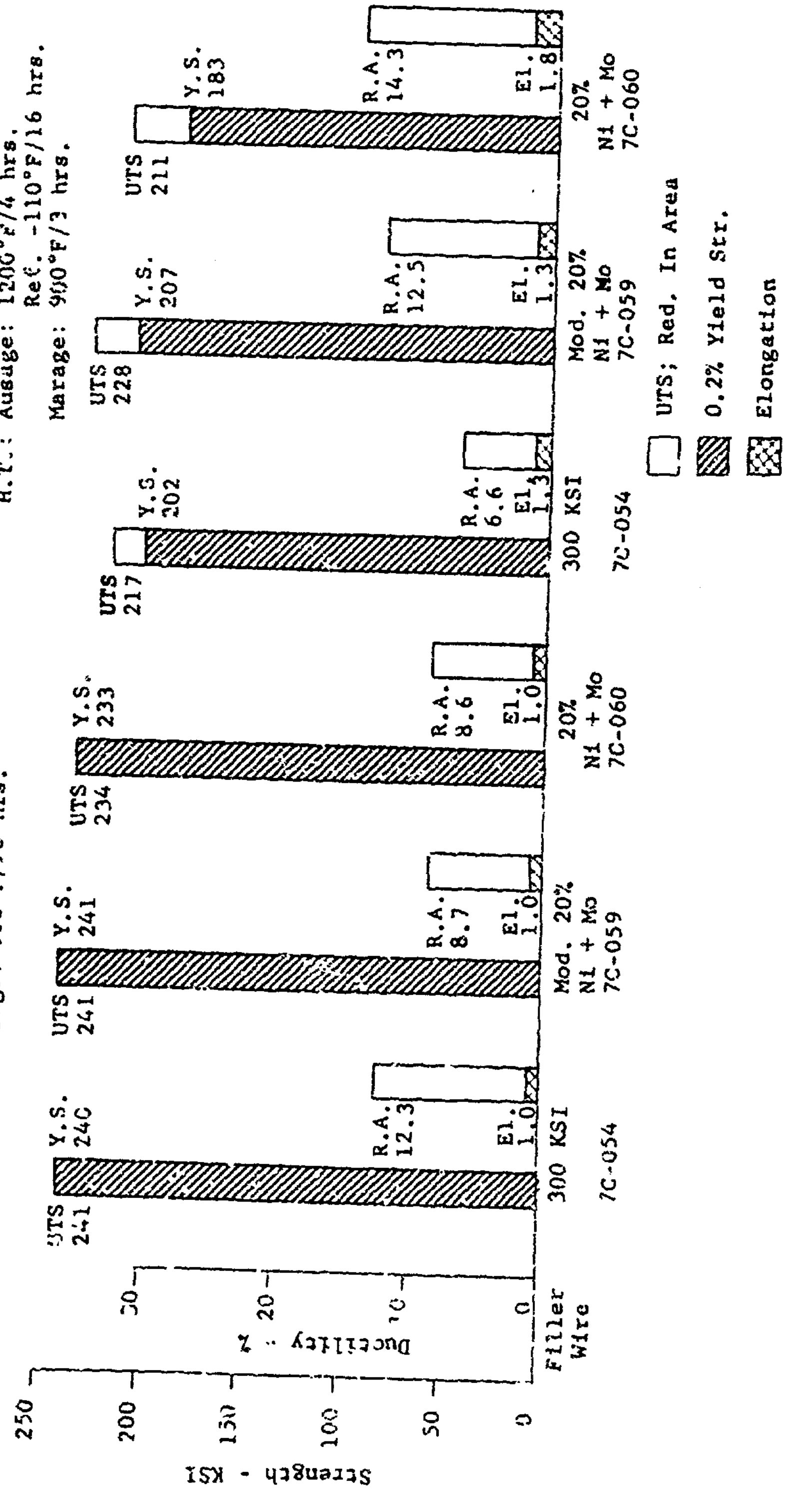

TRANSVERSE WELD TENSILE PROPERTIES
20% AND 25% NI ALLOY - SOLUTION HEAT TREATED (0.070" SHEET)
20% Ni Alloy
H.T.: Marage: 900°F/10 hrs.
25% Ni Alloy
H.T.: Ausage: 1200°F/4 hrs.
Ref. -110°F/16 hrs.
Marage: 900°F/3 hrs.
Strength - KSI
Ductility - %
Filler Wire
UTS 241
Y.S. 240
R.A. 12.3
El. 1.0
300 KSI
7C-054
UTS 241
Y.S. 241
R.A. 8.7
El. 1.0
Mod. 20%
Ni + Mo
7C-059
UTS 234
Y.S. 233
R.A. 8.6
El. 1.0
20%
Ni + Mo
7C-060
UTS 217
Y.S. 202
R.A. 6.6
El. 1.3
300 KSI
7C-054
UTS 228
Y.S. 207
R.A. 12.5
El. 1.3
Mod. 20%
Ni + Mo
7C-059
UTS 211
Y.S. 183
R.A. 14.3
El. 1.8
20%
Ni + Mo
7C-060
UTS; Red. In Area
0.2% Yield Str.
Elongation

Figure 184

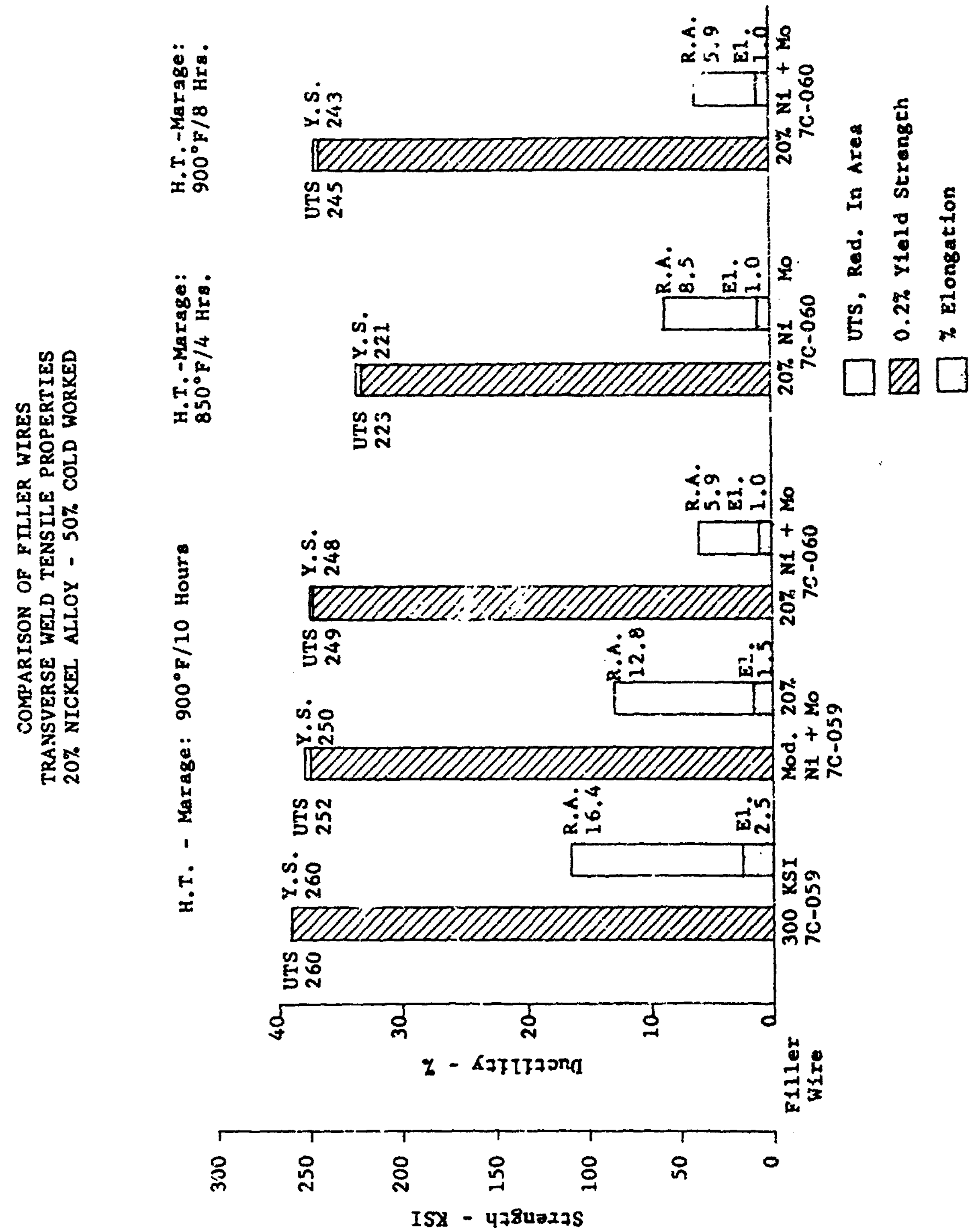
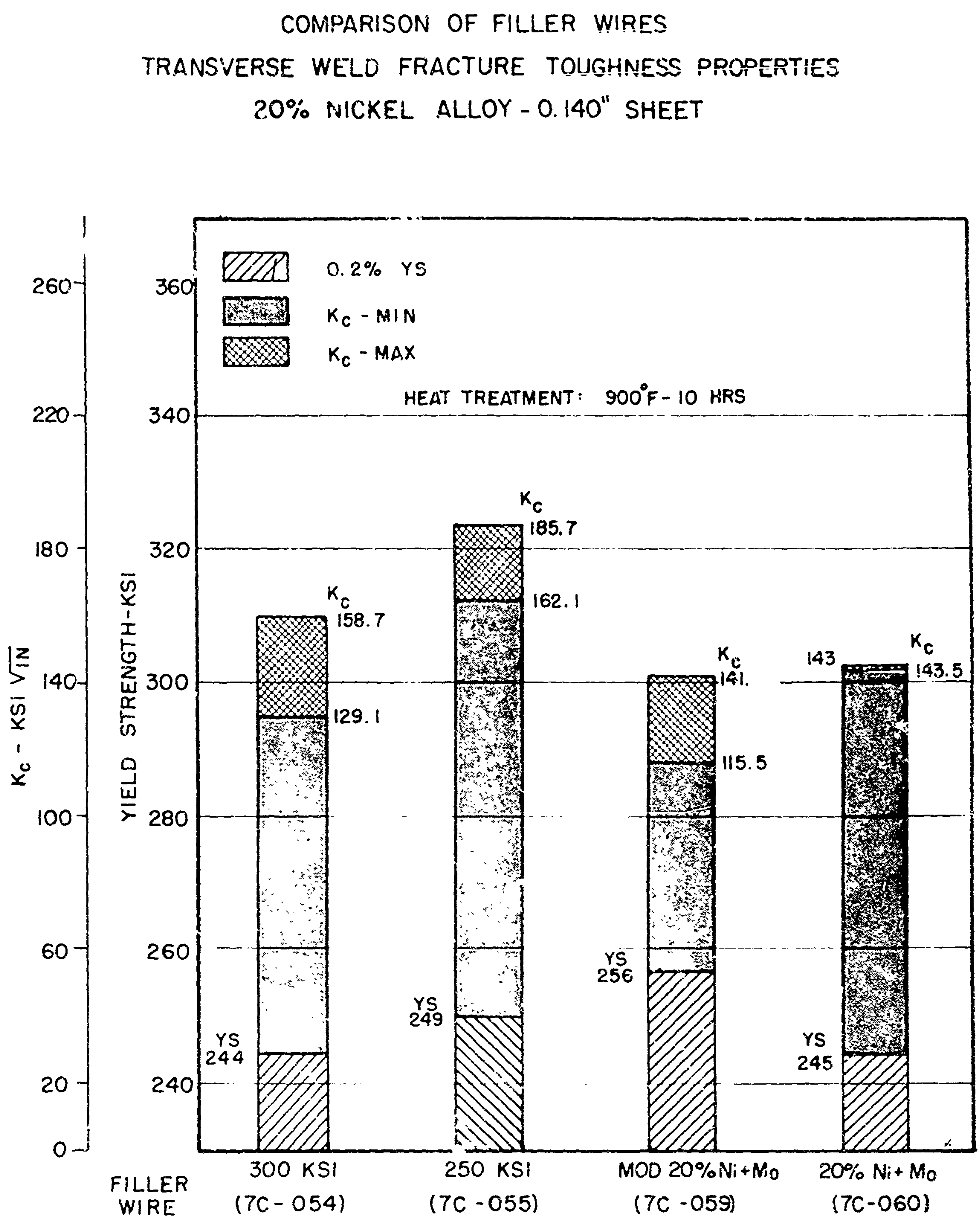
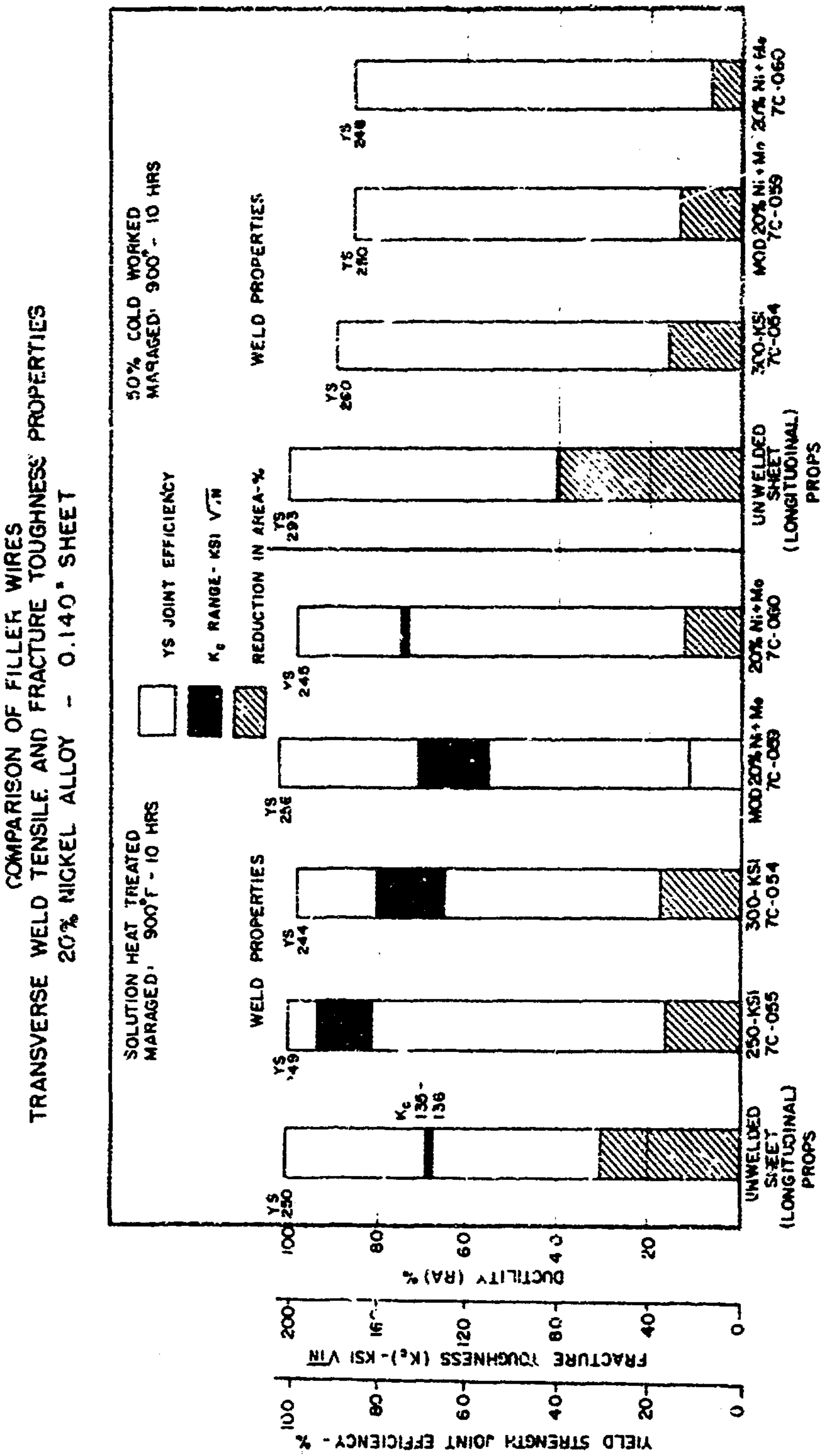

COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE PROPERTIES
20% NICKEL ALLOY - 50% COLD WORKED
H.T. - Marage: 900°F/10 Hours
H.T.-Marage: 850°F/4 Hrs.
H.T.-Marage: 900°F/8 Hrs.
Strength - KSI
Ductility - %
Filler Wire
300 KSI 7C-059
Mod. 20% Ni + Mo 7C-059
20% Ni + Mo 7C-060
20% Ni 7C-060
20% Ni + Mo 7C-060
UTS 260
Y.S. 260
R.A. 16.4
El. 2.5
UTS 252
Y.S. 250
R.A. 12.8
El. 1.5
UTS 249
Y.S. 248
R.A. 5.9
El. 1.0
UTS 223
Y.S. 221
R.A. 8.5
El. 1.0
UTS 245
Y.S. 243
R.A. 5.9
El. 1.0
UTS, Red. In Area
0.2% Yield Strength
% Elongation

Figure 185



COMPARISON OF FILLER WIRES
TRANSVERSE WELD FRACTURE TOUGHNESS PROPERTIES
20% NICKEL ALLOY - 0.140" SHEET
0.2% YS
Kc - MIN
Kc - MAX
HEAT TREATMENT: 900°F - 10 HRS
Kc - KSI √IN
YIELD STRENGTH-KSI
260
220
180
140
100
60
20
0
360
340
320
300
280
260
240
Kc 158.7
129.1
YS 244
Kc 185.7
162.1
YS 249
Kc 141.
115.5
YS 256
143
Kc 143.5
YS 245
FILLER WIRE
300 KSI (7C-054)
250 KSI (7C-055)
MOD 20%Ni+Mo (7C-059)
20% Ni+Mo (7C-060)

Figure 186



COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE AND FRACTURE TOUGHNESS PROPERTIES
20% NICKEL ALLOY - 0.140" SHEET
SOLUTION HEAT TREATED
MARAGED: 900°F - 10 HRS
50% COLD WORKED
MARAGED: 900° - 10 HRS
YS JOINT EFFICIENCY
REDUCTION IN AREA-%
WELD PROPERTIES
WELD PROPERTIES
UNWELDED SHEET (LONGITUDINAL) PROPS
250-KSI 7C-055
300-KSI 7C-054
MOD 20% Ni + Mo 7C-059
20% Ni + Mo 7C-060
UNWELDED SHEET (LONGITUDINAL) PROPS
300-KSI 7C-054
MOD 20% Ni + Mo 7C-059
20% Ni + Mo 7C-060
YS 250
YS 244
YS 256
YS 245
YS 293
YS 260
YS 280
YS 248
DUCTILITY (RA) %
FRACTURE TOUGHNESS (K_c) - KSI $\sqrt{IN}$
YIELD STRENGTH JOINT EFFICIENCY - %

Figure 187

Table 88

EFFECT OF SOLUTIONING TIME AND TEMPERATURE
ON THE HARDNESS OF 20% NI ALLOY*

Solution** Temp. °F	Solution Time Hrs.	As Quenched Hardness Rc	Maraged*** Hardness Rc
1400	¼	39.7	52.0
	½	38.5	51.8
	1	36.5	51.4
	2	35.7	51.3
	4	35.1	51.3
1500	¼	34.2	51.4
	½	30.3	50.0
	1	32.3	51.3
	2	31.2	51.2
	4	31.3	51.1
1600	¼	29.8	50.0
	½	30.9	51.2
	1	30.6	51.2
	2	29.7	50.1
	4	29.2	50.0
1700	¼	29.2	50.1
	½	28.8	49.8
	1	28.6	50.0
	2	30.1	50.1
	4	29.1	50.0
1800	¼	28.4	49.9
	½	28.5	49.9
	1	27.4	49.8
	2	28.6	50.0
	4	28.1	50.1
1900	¼	28.9	50.0
	½	28.5	49.8
	1	29.4	49.5
	2	29.1	49.8
	4	27.8	49.0
2000	¼	28.6	49.6
	½	28.4	49.9
	1	28.4	50.0

Table 88

EFFECT OF SOLUTIONING TIME AND TEMPERATURE
ON THE HARDNESS OF 20% NI ALLOY* (cont'd)

Solution** Temp. °F	Solution Time Hrs.	As Quenched Hardness Rc	Maraged*** Hardness Rc
2000	2	28.1	49.6
	4	27.2	48.8
2100	¼	27.7	48.7
	½	28.1	49.5
	1	29.5	50.1
	2	-	50.0
	4	-	49.7
2200	¼	27.8	48.9
	½	28.2	49.8
	1	27.8	49.6
	2	29.3	50.2
	4	29.6	50.0
2300	¼	29.5	50.1
	½	27.7	48.9
	1	28.6	49.5
	2	27.8	49.2
	4	28.4	50.2

* Allegheny Heat No. 23826

** All specimens maraged @ 900°F for 3 hrs.

*** Average of 6 readings

Table 89

EFFECT OF MARAGING PARAMETERS ON THE HARDNESS OF SOLUTION ANNEALED** 20% NI ALLOY*

Marage Temp.	Marage Time	Hardness*** Rc
800	½	51.4
	1	52.4
	4	51.3
	10	51.3
850	½	50.9
	1	52.0
	4	52.3
	10	52.3
900	½	-
	1	51.5
	4	-
	10	50.5
950	½	51.8
	1	51.6
	4	52.2
	10	51.0

* Allegheny Heat No. 23826

** Solution Anneal: 1500°F/1 hr.

*** Average of 6 readings

Table 90

EFFECT OF SOLUTIONING AND MARAGING PARAMETERS ON LONGITUDINAL TENSILE PROPERTIES OF 20% NICKEL ALLOY *

Sol'n.** Temp. °F	Sol'n. Time Hrs.	Maraging Temp. °F	Maraging Time Hrs.	U.T.S. K.S.I.	0.2% Y.S. K.S.I.	% Elong.	% Red. In Area
1400	½	850	4	264	259	3.0	31
1400	½	850	4	274	269	4.0	29
1400	1	800	½	237	220	8.0	37
1400	1	800	½	239	226	8.0	39
1400	1	900	10				
1400	1	900	10				
1400	1	900	10	235	226	5.0	43
1400	1	900	10	235	228	6.0	39
1400	1	950	3	255	250	8.0	44
1400	1	950	3	259	254	6.0	40
1450	½	900	10	241	246	5.0	34
1450	½	900	10	251	244	6.0	37
1450	1	850	10	286	281	4.0	29
1450	1	850	10	291	286	4.0	35
1450	1	900	3	287	282	5.0	38
1450	1	900	3	286	281	5.0	35
1450	1	900	6	284	280	4.5	29
1450	1	900	6	281	277	4.5	36
1450	1	900	10	258	254	3.0	34
1450	1	900	10	258	256	4.0	35
1450	1	950	5	275	271	5.0	35
1450	1	950	5	275	273	5.0	39

* Allegheny Heat No. 23826

** Levels of interest for solutioning and maraging parameters established from hardness data

Table 9[illegible] (Cont.)
Effect of Solutioning and Maraging Parameters on Longitudinal Tensile Properties of 20% Nickel Alloy

Sol'n.** Temp. °F	Sol'n. Time Hrs.	Maraging Temp. °F	Maraging Time Hrs.	U.T.S. K.S.I.	0.2% Y.S. K.S.I.	Elong.	% Red. In Area
1500	½	900	10	276	269	3.0	18
1500	½	900	10	272	267	4.0	26
1500	1	800	½	206	198	10.0	61
1500	1	800	½	204	186	11.0	62
1500	1	900	10	248	244	3.0	31
1500	1	900	10	257	252	4.0	29
1500	1	950	3	265	258	8.0	58
1500	1	950	3	266	254	8.0	64
1550	½	900	10	273	264	4.0	24
1550	½	900	10	272	269	3.5	28
1550	1	900	10	272	270	3.0	36
1550	1	900	10	271	270	3.5	33
1600	1	800	½	191	165	6.1	27
1600	1	800	½	202	180	7.5	32
1600	1	900	10	275	268	6.5	48
1600	1	900	10	271	262	6.0	43
1600	1	950	3	264	259	7.5	56
1600	1	950	3	264	261	7.5	51

Table 90

TABLE 71

EFFECT OF SOLUTIONING AND MARAGING PARAMETERS ON TRANSVERSE TENSILE PROPERTIES OF 20% NICKEL ALLOY *

Sol'n.** Temp. °F	Sol'n. Time Hrs.	Maraging Temp. °F	Maraging Time Hrs.	U.T.S. K.S.I.	0.2% Y.S. K.S.I.	% Elong.	% Red. In Area
1400	½	850	4	278	271	4.1	18
1400	½	850	4	290	285	3.9	20
1400	1	900	10	250	240	4.0	26
1400	1	900	10	248	238	4.0	29
1400	1	900	10				
1400	1	900	10	250	240	4.0	29
1450	½	900	10	263	254	4.0	16
1450	½	900	10	264	257	3.0	16
1450	1	900	3	301	293	4.0	25
1450	1	900	3	300	295	3.0	24
1450	1	900	6	299	293	3.0	27
1450	1	900	6	297	292	4.0	24
1450	1	900	10	273	268	2.3	23
1450	1	900	10	277	273	3.0	20
1450	1	950	5	299	285	4.0	30
1450	1	950	5	287	282	3.0	34
1500	½	900	10	283	281	4.0	11
1500	½	900	10	282	275	3.0	24
1500	1	900	10	274	269	4.0	25
1500	1	900	10	277	275	3.0	19
1550	½	900	10	284	280	3.0	22
1550	½	900	10	281	280	4.4	25
1550	1	900	10	280	275	3.3	22
1550	1	900	10	295	290	3.5	24
1600	1	900	10	275	270	5.0	41
1600	1	900	10	285	283	5.5	40

* Allegheny Heat No. 23826

** Levels of interest for solutioning and maraging parameters established from hardness data

Table 92

EFFECT OF SOLUTION TREATMENT ON LONGITUDINAL FRACTURE TOUGHNESS OF 20% NICKEL ALLOY *

Solution Temp. °F	Solution Time Hrs.	Maraging Temp. °F	Maraging Time Hrs.	0.2% Yield Str. KSI	Net Fracture Stress (1) KSI	Notch (2) Strength KSI	(3)	Critical Crack Index (4) in	K_c (5) KSI in	G_c(6) in-lb/in^2
1450	1	900	3	251	125	90	1.11	.04	90	292
	1			251	115	82	0.93	.04	82	243
1400	1/2	850	4	264	136	91	1.18	.04	94	323
	"			264	101	75	0.65	.02	72	187
1400	1	900	10	227	214	161	5.93	.21	186	1260
	"			227	228	135	4.47	.16	162	955
	"			227	234	161	7.15	.26	205	1530
	"			227	224	154	5.81	.21	185	1240
1450	1/2			245	208	112	2.37	.09	127	524
	"			245	199	122	3.15	.12	147	784
1450	1			255	183	126	2.56	.09	137	683
	"			255	182	123	2.52	.09	136	671
1500	1/2			268	184	139	2.21	.08	135	663
	"			268	150	98	1.57	.06	106	409
1500	1			248	187	117	2.10	.09	135	663
	"			248	186	114	2.61	.09	136	673
1550	1/2			267	155	107	1.60	.06	114	471
	"			267	136	100	1.22	.04	99	360
1550	1			270	131	96	1.16	.04	95	330
	"			270	124	98	1.02	.04	91	303
1600	1			265	110	83	0.79	.03	80	230
	"			265	135	97	1.22	.04	98	352

* Allegheny Heat No. 23826

Centrally notched, fatigue cracked specimen.

Table 93

EFFECT OF SOLUTION TREATMENT ON TRANSVERSE FRACTURE TOUGHNESS OF 20% NICKEL ALLOY *

Solution Temp. °F	Solution Time Hrs.	Maraging Temp. °F	Maraging Time Hrs.	0.2% Yield Str. KSI	Net Fracture Stress (1) KSI	Notch (2) Strength KSI	(3)	Critical Crack Index (4) in	K_{cI} (5) KSI $\sqrt{in}$	Q_c(F) in-lb/in^2
1450	1	900	3	270	63	58	.23	.01	42	66
				270	65	61	.24	.01	44	72
1400	1/2	850	4	278	76	56	[illegible]	.01	53	105
				278	83	62	.38	.01	58	123
1400	1	900	10	239	173	129	2.76	.10	158	910
				239	183	137	3.10	.11	142	755
1450	1			271	106	72	.70	.02	76	211
				271	104	70	.65	.02	73	196
1500	1/2			278	105	62	.58	.02	70	180
				278	94	67	.48	.02	65	154
1500	1			272	123	80	.87	.03	84	260
				272	121	60	.86	.03	84	258
1550	1			283	81	64	.38	.01	59	126
				283	80	60	.38	.01	57	120
1600	1			277	88	62	.42	.02	61	136
				277	88	61	.42	.02	61	136

* Allegheny Heat No. 23826

Centrally notched, fatigue cracked specimens

Table 94

EFFECT OF MARAGING PARAMETERS ON LONGITUDINAL TENSILE PROPERTIES OF 20% NICKEL ALLOY*

% Reduction	Marage Temp. °F	Marage Time-Hrs.	Ult. Ten. Str.-KSI	0.2% Yield Str.-KSI	% Elong.	% R.A.
20	800	1	291	287	5.0	55
"	"	1	290	287	5.0	54
"	900	1	295	272	5.0	51
"	"	1	294	291	5.0	59
"	"	3	303	299	5.0	38
"	"	3	302	298	5.2	47
"	"	10	301	298	7.0	45
"	"	10	294	289	6.0	52
"	950	1	309	306	4.5	47
"	"	1	305	300	4.8	56
"	"	4	297	295	5.0	56
"	"	4	294	289	5.1	52
30	800	1	297	293	5.0	49
"	"	1	296	296	5.0	54
"	850	1.75	299	296	4.0	37
"	"	1.75	311	306	4.4	36
"	900	1	308	301	3.0	56
"	"	1	311	309	4.0	60
"	"	1.75	309	307	6.0	39
"	"	1.75	315	307	5.0	39
"	"	3				
"	"	3				
"	"	10	298	295	4.9	48
"	"	10	305	299	6.0	44
"	950	1	310	308	1.0	45
"	"	1	305	302	4.2	50
"	"	1.75	301	297	6.0	47
"	"	1.75	302	300	7.0	46
"	"	4	299	293	4.4	52
"	"	4	300	297	4.7	50
40	800	1	285	283	4.0	34
"	"	1	285	284	3.7	38
"	850	1	306	302	4.0	35
"	"	1	310	308	4.1	27
"	"	1.75	300	295	4.4	31
"	"	1.75	314	309	4.4	37
"	900	1	313	304	5.0	39
"	"	1	306	296	4.6	38
"	"	1.75	313	303	6.0	38
"	"	1.75	310	303	6.0	41

Table 94 (Cont.)

EFFECT OF MARAGING PARAMETERS ON LONGITUDINAL TENSILE PROPERTIES OF 20% NICKEL ALLOY*

% Reduction	Marage Temp. °F	Marage Time-Hrs.	Ult. Ten. Str.-KSI	0.2% Yield Str.-KSI	% Elong.	% R.A.
40	900	10	300	295	5.0	43
"	"	10				
"	950	1	302	292	5.0	31
"	"	1	298	293	6.0	38
"	"	1.75	300	291	6.0	49
"	"	1.75	301	294	6.0	42
"	"	4	292	283	5.0	40
"	"	4	296	287	5.0	41
50	800	1	295	293	5.0	52
"	"	1	297	295	5.0	64
"	850	1.75	309	306	4.5	31
"	"	1.75	310	303	5.0	28
"	900	1	303	302	5.0	48
"	"	1	304	303	5.0	47
"	"	1.75	303	296	7.0	38
"	"	1.75	291	289	5.0	31
"	"	3	311	308		
"	"	3				
"	"	10	295	293	4.0	40
"	"	10				
"	950	1.75	298	295	9.0	48
"	"	1.75	300	295	6.0	37
"	"	4	300	295	6.0	58
"	"	4	303	298	4.9	49
70	800	1	274	272	5.0	30
"	"	1	281	279	5.0	29
"	850	1	304	299	4.6	31
"	"	1	291	288	4.8	34
"	900	1	300	293	4.5	37
"		1	296	289	4.8	36
"		3	297	284	3.0	22
"		3	311	304	5.0	34
"		10	294	293	5.0	42
"		10	300	292	4.9	36
"	950	1	296	286	5.0	42
"	"	1	298	293	5.0	39
"	"	4	290	281	6.0	40
"	"	4	276	273	5.0	25

* Allegheny Heat No. 23826

Table 95

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON THE TRANSVERSE TENSILE PROPERTIES OF 20% NICKEL ALLOY

% Reduction	Marage Temp. °F	Marage Time Hrs.	Ultimate Tensile Strength KSI	0.2% Yield Strength KSI	% Elong.	% R.A.
20	900	3	319	316	5.0	36
	"	"	310	310	5.0	27
	"	10	311	298	5.0	34
	"	"	300	300	4.0	31
30	850	1.75	326	320	5.0	24
	"	"	327	319	4.0	23
	950	"	317	315	3.1	26
	"	"	322	312	2.2	17
	900	3	324	323	3.0	2
	"	"	324	324	4.0	23
	"	10	320	296	3.0	12
	"	"	310	310	4.0	19
40	850	1.75	338	337	3.0	17
	"	"	323	316	3.0	17
	950	"	329	326	2.5	15
	"	"	314	309	1.7	27
	900	3	320	315	3.0	12
	"	"	319	319	2.0	9
	"	10	311	300	4.0	16
	"	"	329	321	4.0	18
50	850	1.75	324	317	3.0	17
	"	"	325	320	5.0	24
	900	"	327	319	3.0	23
	"	3	302	294	3.0	7
	"	"	304	304	3.0	6
	"	10	329	329	4.0	8
	"	"	315	302	3.0	6
70	900	3	316	316	3.0	6
	"	"	312	312	3.0	5
	"	10	320	308	3.0	14
	"	"	325	315	3.0	14

* Allegheny Heat No. 23826

Table 96

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON LONGITUDINAL FRACTURE TOUGHNESS OF 20% NICKEL ALLOY*

Per-cent Reduction	Maraging Temp. °F	Maraging Time Hrs.	0.2% Yield Str. KSI	Net Fracture Stress(1) KSI	Notch Strength(2) KSI	β (3)	Critical Crack Index(4) In.	Kc (5) KSI $\sqrt{In}$	Gc (6)+ In-lbs/in^2
20	900	10	294	194	151	2.05	0.080	146	791
			294	192	153	2.03	0.079	146	777
	950	1	303	191	136	1.65	0.066	138	687
30	900	1 3/4	307	171	115	1.23	0.048	119	516
			307	172	114	1.25	0.049	120	525
	900	10	297	150	123	1.17	0.044	111	446
			297	176	121	1.47	0.057	125	571
	950	1	305	191	125	1.67	0.062	134	654
40	900	1 3/4	303	173	104	1.14	0.044	112	458
			303	144	96	0.91	0.034	99	361
	950	1	292	190	109	1.39	0.053	119	516
			292	186	127	1.69	0.064	131	628
			292	197	126	1.91	0.069	136	674
			292	183	129	1.66	0.064	131	621
50	900	1 3/4	292	155	102	1.07	0.043	107	420
	950	1	312	185	111	1.22	0.048	121	533
			312	207	123	1.50	0.059	134	651
			312	212	121	1.58	0.064	140	712
			312	207	120	1.56	0.061	136	674
70	900	1 3/4	289	151	98	1.13	0.042	105	398
	900	10	293	151	96	1.33	0.052	118	507
			293	172	97	1.22	0.048	114	469
	950	1	289	202	111	1.70	0.065	129	604

* Allegheny Heat No. 23826

\+ Centrally notched, fatigue cracked specimens

Table 97

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON TRANSVERSE FRACTURE TOUGHNESS OF 20% NICKEL ALLOY*

% Reduction	Maraging Temp. °F	Maraging Time Hrs.	0.2% Yield Str. KSI	Net Fracture Stress(1) KSI	Notch Str. (2) KSI	β (3)	Critical Crack Index In. (4)	Kc (5) KSI $\sqrt{In}$	Gc (6)+ In-lbs/in^2
20	900	3	313	121	78	0.56	0.023	83.5	253
		"	313	106	76	0.47	0.019	75.5	207
		10	239	127	87.7	0.68	0.027	86.9	274
		"	299	109	82.5	0.55	0.022	78.0	223
30		3	324	90.4	67.8	0.33	0.013	65.0	154
		"	324	83.3	63.5	0.28	0.011	60.3	132
		10	303	99.2	74.0	0.45	0.018	71.2	184
		"	303	116	77.[illegible]	0.58	0.023	80.0	236
40		3	317	75.0	58.0	0.24	0.009	54.2	107
		"	317	75.0	56.8	0.24	0.009	54.2	107
		10	311	97.0	62.3	0.37	0.014	66.0	158
		"	311	86.0	67.0	0.34	0.013	62.4	141
50		3	299	91.3	53.0	0.29	0.011	56.0	115
		"	299	85.6	62.0	0.33	0.013	60.8	135
		10	316	106	65.0	0.38	0.015	68.3	169
		"	316	90.0	70.0	0.35	0.014	65.2	155
70		3	314	59.5	46.8	0.15	0.006	42.6	66
		"	314	66.2	52.0	0.19	0.007	47.3	81
		10	310	73.0	48.0	0.21	0.008	49.2	88
		"	310	71.8	58.9	0.20	0.008	52.0	97.6

* Allegheny Heat No. 23826

\+ Centrally notched, fatigue cracked specimens

Table 98

LONGITUDINAL TENSILE PROPERTIES OF
WARM WORKED 20% NICKEL ALLOY*

Warm Work Temp. °F	Marage Temp. °F	Marage Time Hours	Ult. Ten. Str. KSI	0.2% Yield Str. KSI	% Elong	% R.A.
1200	850	1	239	225	11.0	53
"	850	1	233	219	10.0	46
"	850	1 3/4	228	214	11.0	49
"	850	1 3/4	235	220	10.0	50
"	900	1 3/4	228	212	9.0	55
"	900	1 3/4	231	216	12.0	52
"	900	3	227	221	9.0	38
"	900	3	242	227	8	53
"	900	10	232.3	215.4	9.0	37
"	900	10	233.2	215.5	7.5	37
"	950	1 3/4	224	207	13.0	55
"	950	1 3/4	213	205	13.0	70
1400	850	1	271	261	5.0	46
"	850	1	264	250	6.0	34
"	850	1 3/4	260	245		
"	850	1 3/4	262	260	7.0	40
"	900	1 3/4	275	262	7.0	56
"	900	1 3/4	283	271	7.0	48
"	900	3	281	269	5.0	44
"	900	3	290	284	6.0	48
"	900	10	287	278.6	5.0	39
"	900	10	284.1	272.4	5.0	32
"	950	1 3/4	278	266	9.0	47
"	950	1 3/4	265	257	11.0	43
1600	850	1	237	229	1.6	9
"	850	1	241	228	3.1	12
"	850	1 3/4	210	210	3.0	4
"	850	1 3/4	214	211	3.0	9
"	900	1 3/4	261	244	5.0	32
"	900	1 3/4	264	252	6.0	33
"	900	3	260	245	4.0	27
"	900	3	271	255	5.0	30
"	900	10	271.6	255.6	5.0	33
	900	10	275	262.7	5.0	27
"	950	1 3/4	263	251	5.0	43
"	950	1 3/4	267	252	7.0	49

Table 99

TRANSVERSE TENSILE PROPERTIES OF WARM WORKED 20% NICKEL ALLOY

Warm Work Temp. °F	Marage Temp. °F	Marage Time-Hrs.	Ult. Ten. Str.-KSI	0.2% Yield Str.-KSI	% Elong.	% R.A.
1200	850	1 3/4	233	214	4.5	32
1200	850	1 3/4	236	218	4.3	37
1200	900	1 3/4	238	224	12.0	38
1200	900	1 3/4	242	224	9.0	43
1200	900	10	238.8	223.1	9.0	31
1200	900	10	240.8	224.2	9.0	30
1200	950	1 3/4	220	215	11.0	39
1200	950	1 3/4	222	212	8.0	42
1500	850	1 3/4	268	257	6.0	34
1500	850	1 3/4	270	258	7.0	38
1500	850	10	295	281	5.0	40
1500	850	10	294	282	4.0	42
1500	900	1 3/4	284	276	6.0	56
1500	900	1 3/4	287	279	5.0	38
1500	900	10	291.1	281	4.5	35
1500	900	10	288.7	281.6	4.0	29
1500	950	1 3/4	283	281	6.0	48
1500	950	1 3/4	296	286	5.0	44
1800	850	1 3/4	171	171	1.1	5
1800	850	1 3/4	178	178	1.1	6
1800	900	1 3/4	255	245	5.0	32
1800	900	1 3/4	253	235	6.0	37
1800	900	10	275.7	262	4.5	28
1800	900	10	277.1	262	5.0	33
1800	950	1 3/4	268	256	7.0	60
1800	950	1 3/4	267	258	6.0	50

Allegheny Heat No. 23826

Table 100

EFFECT OF MARAGING TREATMENT ON FRACTURE TOUGHNESS
OF WARM WORKED 20% NICKEL ALLOY *

Warm Working Temp. °F	Orientation Of Specimen Axis To Rolling Direction	Maraging Temp. °F	Maraging Time, Hrs.	0.2% Yield Str. KSI	Net Fracture Stress (1) KSI	Notch (2) Strength KSI	ρ (3)	Critical Crack (4) Index .in	K_c KSI $\sqrt{.in}$ (5)	G_c (6) + .in-lb/in^2
1200	Parallel	900	10	206	214	197	8.05	0.28	193	1350
			"	206	238	198	11.11	0.42	236	2030
1400			3	280	176	121	0.18	0.07	128	600
			"	280	174	122	0.19	0.07	127	590
			10	262	147	113	0.15	0.06	109	430
			"	262	155	109	0.16	0.06	114	470
	Normal		3	289	111	92	0.07	0.03	81	129
			"	289	177	[illegible]	0.08	0.03	91	144
			10	237	130	[illegible]	0.09	[illegible]	96	152
			"	287	116	92	0.07	0.33	[illegible]	134
1600	Parallel		10	265	192	137	2.59	0.95	145	760
			"	265	188	129	2.46	0.91	142	735

* Allegheny Heat No. 23526

+ Centrally notched, fatigue cracked specimen

Table 10[illegible]

HEAT TREAT RESPONSE OF A THICK SECTION**
OF 20% NICKEL ALLOY*

Specimen Location in Cube***	U.T.S. KSI	0.2% Yield Str.	% Elong.	Red. In+ Area %
Surface	221	****	0.0	0.6
	276	264	1.5	3.2
Center	252	****	0.5	0.6
	202	****	0.5	-

* Allegheny Heat No. 23826

** Cube dimensions: 4½" x 4½" x 5¼"

*** Specimens machined parallel to flow lines at both locations

\+ H.T.: Soln: 1450°F/1 hr.
Marage: 900°F/10 hrs.

(1 hr/in. thickness allowed at respective temperatures)

**** Brittle failure

TABLE 102

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 20% NICKEL ALLOY

Location	% Reduction	Heat Treatment	U.T.S. (KSI)	0.2% Y.S. (KSI)	% Elong.	% R.A.
Billet						
Vertical-Center	0	1450°F/1 hr.	257.9	247.9	10.5	49.9
Vertical-Edge	0	900°F/10 hrs.	266.8	257.5	10	46.5
Horizontal-Center	0		189.5	Broke at Gage Mark		
Horizontal-Edge	0		272.6	256.4	2.5	4.5
First Upset						
Vertical-Center	33.8		258.1	242.1	1.8	37.6
Vertical-Edge	33.8		271.7	256.4	1.9	40.6
Horizontal-Center	33.8		276.6	258.9	1.4	9.4
Horizontal-Edge	33.8		274.3	244.1	1.7	13
Second Upset						
Vertical-Center	50		258.9	253.1	1.3	16
Vertical-Edge	50		272.9	257.3	1.9	38.9
Horizontal-Center	50		183.0	Broke at Gage Mark		
Horizontal-Edge	50		259.9	257.7	1.3	13.6
Third Upset						
Vertical-Center	66.2		260.3	248.5		2.7
Vertical-Edge	66.2		271.3	251.5		
Horizontal-Center	66.2		213.1			
Horizontal-Edge	66.2		274.9	259.5	1.8	24.4
Fourth Upset						
Vertical-Center	75		234.9		1.2	3
Vertical-Edge	75		272	269.8	9.3	51
Horizontal-Center	75		161.3	Broke at Gage Mark		
Horizontal-Edge	75		271.5	254.5	1.8	3.5
Fifth Upset						
Vertical-Center	84		226.3		1.2	3.6
Radial	84		272.3	266.7	10.5	48.7
Circumference	84		272	261.6	10	42.9

Table 103

Critical Fracture Toughness
Parameters of 20% Nickel Alloy *

Condition	Heat Treat	N.T.S. KSI	K_{1C} KSI $\sqrt{in}$	G_{1C}** in-lb/in^2	$\frac{NTS}{UTS}$
Annealed	Sol'n.: 1450°F/1 Hr.	364.4	75.5	207.3	1.43
	Marage: 900°F/10 Hrs.	345.7	71.5	186.0	1.35
		324.7	67.3	164.5	1.27
30% Cold Work	Marage: 900°F/10 Hrs.	340.8	70.6	183.4	1.13
		336.1	69.6	176.1	1.11
40% Cold Work		341.3	70.6	181.7	1.14
		340.2	70.5	181.0	1.14
50% Cold Work		345.5	71.5	186.0	1.17
		344.9	71.4	185.3	1.17

* Allegheny Heat No. 23826

** Critical fracture toughness estimated from circumferentially-notched tensile bars (K_t = 10).

*** $\frac{N.T.S.}{U.T.S.}$ ratio estimated from U.T.S. of sheet stock.

Table 104

WELD HARDNESS DATA - DPH (1)
20% NICKEL ALLOY - VERTICAL TRAVERSES (2)

Filler Wire Condition (3)	250 KSI (7C-055)		Mod. 20% Ni (7C-058)		Mod. 20% Ni + Mo (7C-059)		20% Ni + Mo (7C-060)	
	As-Welded	Maraged	As-Welded	Maraged	As-Welded	Maraged	As-Welded	Maraged
Distance from Top of Weld In.								
.020	332	466	318	484	310	468	338	479
.040	329	451	322	482	324	464	320	453
.060	316	460	312	484	314	472	312	460
.080	316	464	316	451	307	468	319	446
.100	318	454	318	461	341	453	312	490
.120	310	438	332	488	345	497	327	507
.140	336	507	330	517	340	501	330	475
.160	341	483	332	505	339	497	323	497
.180	347	505	350	486	341	486	340	481
.200	341	488	357	490	318	490	357	453
.220	--	466	--	--	--	--	--	--
Average-DPH	328.6	471.5	328.7	484.8	327.9	479.6	327.8	474.1
Rc (Converted)	33.4	47.0	33.4	47.9	33.3	47.5	33.3	47.0

(1) Diamond Pyramid Hardness - 10 KG load, 136° apex angle

(2) Vertical traverse - top to bottom along weld centerline

(3) Maraged: 850°F/4 hrs.

Table 105

WELD HARDNESS DATA

20 and 25% NICKEL ALLOY - HORIZONTAL TRAVERSE (1)

Base Material	Filler Wire	Condition (3)	Hardness - DPH (2) Distance from Weld Centerline - In. 0	.020	.040	.060	.080	.100	.120	.140	Average DPH	Average Rc (Converted)
20% Nickel	7C-055	As-Welded	310	315	316	318	326	314	320	322	318	32
		Aged	507	492	497	482	479	499	503	511	496	48.7
	7C-058	As-Welded	318	322	312	316	318	332	330	--	321	32.5
		Aged	484	482	484	451	461	488	517	--	481	47.5
	7C-059	As-Welded	345	336	334	335	332	339	341	--	337	34.5
		Aged	497	515	513	490	507	513	525	--	508.5	49.6
	7C-060	As-Welded	338	320	312	319	312	327	--	--	321	32.5
		Aged	479	453	460	446	490	507	--	--	472.5	47
25% Nickel	7C-055	As-Welded	294	306	310	315	299	305	311	288	303.5	30.5
		Aged	527	551	540	551	542	555	574	551	549	52.3
	7C-058	As-Welded	332	314	310	307	313	279	265	--	303	30.3
		Aged	540	525	525	521	533	562	562	--	538	50.3
	7C-059	As-Welded	258	261	268	265	261	255	--	--	261	24.5
		Aged	533	525	551	546	529	544	--	--	538	50.3
	7C-060	As-Welded	304	291	291	286	251	256	258	--	277	27
		Aged	515	511	511	507	538	560	565	--	529.5	51

(1) Traverse taken along weld midpoint line

(2) Diamond Pyramid Hardness, 10 KG load, 136° apex angle

(3) Aged: 20% Nickel, 850°F/4 hrs.

25% Nickel, 1300°F/4 hrs., Air Cool & Ref. - 110°F/16 hours + 850°F/4 hours

Table 106

WELD HEAT AFFECTED ZONE HARDNESS DATA - DPH (1)
20% NICKEL ALLOY - HORIZONTAL TRAVERSE (2)

Base Material	Condition(3)	Distance From Weld Interface - In. .015	.030	.045	.060	.075	.090	.105	.120	.135	.150	.165	.180	.195	.210	.225	.240	.255	.270	.285	.300	.315	.340	.365	.390	.415	.440
Solution Heat Treated	As-Welded	323	340	357	327	328	342	331	329	327	327	338	338	343	333	331	340	347	371	426	456	527	423	365	359	356	-
	Aged	497	481	453	507	482	490	482	475	477	484	507	519	495	499	515	525	536	555	569	558	560	548	544	536	544	540
50% Cold Worked	As-Welded	315	304	301	322	315	332	315	365	411	432	560	614	542	-	484	-	451	-	426	-	426	414	417	397	402	-
	Aged	606	583	583	583	619	583	560	495	567	-	588	-	575	-	567	-	-	-	-	-	-	-	-	-	-	-

(1) Diamond Pyramid Hardness, 10KG load, 136° apex angle

(2) Traverse taken along sheet centerline

(3) Aged: 850°F/4 hrs.

Table 107

TRANSVERSE WELD TENSILE PROPERTIES
20% NICKEL ALLOY - SOLUTION HEAT TREATED 0.140" SHEET (1) (2)

FILLER WIRE		MARAGE						AVERAGE PROPERTIES					
Type	Heat No.	Temp °F	Time Hrs.	UTS KSI	0.2% YS KSI	Elong %	R.A. %	UTS KSI	0.2% YS KSI	Elong %	R.A. %	Joint Eff. % TS	Joint Eff. % YS
250 KSI	7C-055	850	4	219	219	1.0	4	223	223	1.0	7	83	84
				227	227	1.0	10						
		900	10	252	249	2.0	13.8	250	249	2.25	15.7	98	100
				248	248	2.5	17.5						
300 KSI	7C-054	900	10	245	243	1.5	16.7	247	244	1.3	--	97	98
				248	245	1.0	3.3						
MOD. 20% Ni	7C-058	850	4	182	182	0.7	3	178	178	0.7	3	66	67
				173	173	0.7	3						
MOD. 20% Ni + Mo	7C-059	850	4	226	226	1.0	5	222	222	.95	4.5	83	84
				217	217	0.9	4						
		900	10	256	255	2.0	11.7	258	256	2.0	12.1	101	102
				259	257	2.0	12.4						
20% Ni + Mo	7C-060	850	4	222	222	2.0	10	225	222	1.5	10	84	84
				228	222	1.0	10						
		900	10	245	242	1.5	14.1	248	245	1.5	13.2	97	98
				250	247	1.5	12.2						

(1) Sheet rolling direction parallel to orientation of specimen axis.

(2) All specimens failed in weld.

Table 108

TRANSVERSE WELD TENSILE PROPERTIES
20% AND 25% NICKEL ALLOY SOLUTION HEAT TREATED 0.070" SHEET (1)

Base Material	Filler Wire Type	Filler Wire Heat No.	Ausage (2) Temp. °F	Ausage (2) Time Hrs.	Marage Temp. °F	Marage Time Hrs.	U.T.S. KSI	0.2% Y.S. KSI	Elong. %	R.A. %	Average Properties U.T.S. KSI	Average Properties 0.2% Y.S. KSI	Average Properties Elong %	Average Properties R.A. %	Joint Eff.-% T.S.	Joint Eff.-% Y.S.
20% Nickel	300 KSI	7C-054	-	-	900	10	235 (3)	238	1.0	17.2	241	240	1.0	12.3	82	82
							242 (3)	241	1.0	7.4						
	Mod. 20%Ni+Mo	7C-059	-	-	900	10	245 (3)	245	1.0	3.2	241	241	1.0	8.7	82	82
							237	236	1.0	14.2						
	20% Ni+Mo	7C-060	-	-	900	10	234 (3)	233	1.0	8.6	234	233	1.0	8.6	79	80
25% Nickel	300 KSI	7C-054	1200	4	900	3	217 (4)	205	1.0	3.9	217	202	1.3	6.6	75	76
							217 (4)	198	1.5	9.2						
	Mod. 20%Ni+Mo	7C-059	1200	4	900	3	232 (4)	215	1.0	6.1	228	207	1.3	12.5	79	78
							224	203	1.5	18.8						
	20%Ni+Mo	7C-060	1200	4	900	3	213 (4)	179	2.0	13.5	211	183	1.8	14.3	73	69
							205 (4)	196	1.5	5.1						

(1) Sheet rolling direction parallel to orientation of specimen axis
(2) All 25% Nickel alloy specimens refrigerated after ausaging 16 hrs. at -110°F.
(3) Specimens failed in weld and heat affected zone.
(4) Specimens failed in heat affected zone only.

Table 109

TRANSVERSE WELD TENSILE PROPERTIES
20% NICKEL ALLOY - 50% COLD WORKED 0.140" SHEET (1) (2)

Filler Wire		Marage						Average Properties					
Type	Heat No.	Temp. °F	Time Hours	U.T.S. KSI	0.2% Y.S. KSI	Elong. %	R.A. %	U.T.S. KSI	0.2% Y.S. KSI	Elong. %	R.A. %	Joint Eff-% T.S.	Joint Eff-% Y.S.
300 KSI	7C-054	900	10	259	259	2.5	20.0	260	260	2.5	16.4	87	89
				261	261	2.5	12.7						
Mod.20% Ni+Mo	7C-059	900	10	252	250	1.5	12.8	252	250	1.5	12.8	85	85
20% Ni+Mo	7C-060	850	4	222	220	0.9	8.0	223	221	1.0	8.5	75	75
				223	221	1.1	9.0						
		950	8	241	241	1.7	19.0	245	243	2.0	21.5	83	83
				247	244	2.3	24.0						
		900	10	252	250	1.0	4.2	249	248	1.0	5.9	84	85
				246	245	1.0	7.4						

(1) Sheet rolling direction parallel to orientation specimen axis.

(2) All specimens failed in weld.

TABLE 110

TRANSVERSE WELD FRACTURE TOUGHNESS PROPERTIES
20% NICKEL ALLOY - 0.14C" SHEET

FILLER WIRE TYPE	FILLER WIRE HEAT NO.	MARAGE TEMP. (^{o}F)	MARAGE TIME (hrs.)	0.2% YIELD STR. (KSI)	NET FRACTURE STRESS (KSI)	NOTCH STRENGTH (KSI)	β	CRITICAL CRACK INDEX (in)	K_c KSI $\sqrt{in}$	G_c in-lb/in^2
300 KSI	7C-054	900	10	244	198.3	116.6	2.41	.089	129.1	606.2
				244	213.6	139.1	3.71	.135	158.7	915.8
250 KSI	7C-055	900	10	249	203.5	164	3.82	.135	162.1	955.5
				249	235.9	164.6	4.88	.177	185.7	1254
MOD.20% Ni / Mo	7C-059	900	10	256	187.7	133.7	2.56	.097	141.2	724.8
				256	152.9	125.5	2.00	.065	115.5	485.4
20% Ni / Mo	7C-060	900	10	245	185.4	133.4	3.01	.108	143	743.3
				245	191.6	133.7	2.91	.109	143.5	749.3

Table 111

COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE AND FRACTURE TOUGHNESS PROPERTIES
20% NICKEL ALLOY

Base Material		Filler Wire		Marage		Average Weld Properties							Unwelded Sheet Properties					
										Joint Efficiency-%							K_c - KSI $\sqrt{in.}$	
Condition	Thickness in.	Type	Heat No.	Temp. °F	Time Hours	UTS KSI	0.2% Y.S. KSI	Elong. %	R.A. %	TS	Y.S.	K_c KSI $\sqrt{in}$	UTS KSI	0.2% Y.S. KSI	Elong. %	R.A. %	Longitudinal	Transverse
Solution Heat Treated (1)	0.140	250 KSI	7C-055	900	10	250	249	2.25	15.7	98	100	162-186	255	250	3.5	30.0	135-136	84
		300 KSI	7C-054	900	10	247	244	1.3	16.7	97	98	129-139						
		Mod. 20% Ni + Mo	7C-059	900	10	258	256	2.0	12.1	101	102	115-141						
		20% Ni + Mo	7C-060	900	10	248	245	1.5	13.2	97	98	143-144						
50% Cold Worked	0.140	300 KSI	7C-054	900	10	260	260	2.5	16.4	87	89	-	295	293	4.0	40.0	-	65-68
		Mod. 20% Ni + Mo	7C-059	900	10	252	250	1.5	12.8	85	85	-						
		20% Ni + Mo	7C-060	900	10	249	248	1.0	5.9	84	85	-						
Solution Heat Treated (1)	0.070	300 KSI	7C-054	900	10	241(2)	240	1.0	12.3	82	82	-						
		Mod. 20% Ni + Mo	7C-059	900	10	241(2)	241	1.0	6.7	82	82	-						
		20% Ni + Mo	7C-060	900	10	234(2)	233	1.0	5.6	79	80	-						

(1) Unwelded sheet solution heat treated 1500°F/1 hour

(2) Specimens failed in weld and heat-affected-zone

3.0 25% NICKEL ALLOY

3.1 Solution Annealed Condition

The effects of solution, ausage, refrigeration and marage temperature and time combinations on the hardness, strength and toughness of the 25% nickel alloy were evaluated. The results of this work are described in the following sections.

3.1.1 Effect of Solution, Ausage, Refrigeration and Maraging Parameters on Hardness

The effects of solution time and temperature on both "as-quenched" and fully heat treated hardness are reported in Table 112. Fully heat treated hardness was obtained by ausaging 1300°F/4 hours, refrigerating -110°F/16 hours and maraging 900°F/3 hours. As-quenched hardness was obtained by the treatments indicated. It is shown in Figures 112 and 113 that as-quenched hardness drops significantly from 1300°F (Ra 68.4 to 69.9) to 1700°F (Ra 42 to 45.5). Short times (½ hour) at 1800°F and 1900°F also produced minimum hardness. For temperatures above 1700°F and times of 1 to 4 hours, hardness increases. The probable cause for this occurrence is that the high temperatures allow greater grain growth, increasing the M_S temperature and dwell time on cooling through the precipitation range of Fe_2Ti type compounds. It is shown that the hardness response of specimens solutioned at the high temperatures is slightly lower than the response of specimens solutioned from 1300°F to 1700°F. The preferred solution temperature range lies between 1500°F to 1700°F as shown in Figure 112.

The effect of ausaging temperature and time on as-quenched hardness and fully heat treated hardness is reported in Table 113. As-quenched hardness after ausaging is plotted in Figure 190. Fully heat treated hardness reported in Table 113 was obtained by solutioning at 1500°F/1 hour, ausaging as indicated, refrigerating at -110°F/16 hours and maraging at 900°F/3 hours. The maximum maraged hardness was obtained by 1300°F and 1400°F maraging treatments. As-quenched 1400°F hardness indicates for less transformation to martensite than the 1300°F treatment.

Refrigeration temperature and its effects on hardness were determined on specimens solutioned at 1500°F/1 hour, ausaged 1300°F/4 hours, refrigerated as indicated in Table 114 and maraged at 900°/3 hours. All three temperatures produced the desired hardness response after maraging. Retained austenite studies conducted on the refrigerated specimens indicated less than 1% retained austenite.

The effects of maraging temperature and time on hardness after solutioning at 1500°F/1 hour, ausaging at 1300°F/4 hours, refrigerating at 110°F/16 hours and maraging as indicated are reported in Table 5.5.4. As illustrated in Figure 5.5.4, the maximum hardness response was obtained from 800°F and 900°F maraging temperatures. The response obtained by the 900°F treatment was considered slightly superior.

3.1.2 - Effect of Solutioning, Ausaging and Maraging Parameters on Tensile Properties

Longitudinal and transverse tensile properties, as produced by various combinations of solution, ausage and marage temperatures and times are tabulated in Tables 116 and 117. The yield strength results of this study are plotted in Figures 192 and 193. Peak longitudinal yield strength was achieved for a solution temperature of 1500°F/1 hour, ausage at 1200°F/1 hour and 900°F/3 hour marage. The longitudinal yield strength reached an average of 268 KSI. Transverse specimens heat treated similarly, produced the average value of 276 KSI. The corresponding ductility values were low, averaging 4% elongation, 20% R.A. for longitudinal specimens and 3.5% elongation, 12.5% R.A. for transverse specimens. Solutioning at 1600°F and ausaging at 1300°F/4 hours reduced yield strengths by approximately 5 KSI but improved ductility substantially (30% RA).

3.1.3 Effect of Solutioning and Ausaging Parameters on Fracture Toughness

The effects of solution and ausaging temperature on the fracture toughness parameters for the longitudinal and transverse directions are reported in Tables 118 and 119. The longitudinal and transverse fracture toughness parameter K_c, as a function of solution and ausaging temperature is plotted in Figure 194. The highest average longitudinal K_c value (185 KSI $\sqrt{in}$) was obtained for a 1450°F/½ hour solution treatment, 1200°F/4 hour ausage -110°F refrigeration and 900°F/3 hour marage. The yield strength for this heat treatment was 225 KSI.

3.2 Cold Worked Condition

3.2.1 Effect of Cold Work on Tensile Properties

The effects of cold work on tensile properties were determined initially by eliminating the refrigeration treatment and maraging directly. The longitudinal and transverse tensile properties and percentage of retained austenite are reported in Tables 120 and 121. Figures 195 and 196 represent the longitudinal and transverse yield strengths as a function of cold work level and maraging

temperature. It is shown that as cold work level increases, yield strength increases, since the transformation to martensite becomes more complete. Table 120 shows that at 30% cold work, the amount of retained austenite detected was 17.3%. At 40% cold work, the amount of retained austenite had dropped to 9.2%. The 50% cold work level produced a low of 3.7% retained austenite. Table 122 and Figure 121 report the isochronal transformations of retained austenite in the 25% nickel alloy. It is shown that a refrigeration treatment of -110°F/15 minutes almost completely transforms any retained austenite after ausaging.

The effects of cold work and maraging parameters including an intermediate refrigeration treatment of -110°F/16 hours, on longitudinal and transverse tensile properties are presented in Table 123 and 124. Figures 198 and 199 present the longitudinal and transverse yield strengths as a function of cold work level and maraging time at 900°F. The maximum longitudinal yield strength of 242 KSI was achieved for the 50% cold work material maraged at 900°F/3 hours. The corresponding transverse yield strength was 266 KSI. These values compare to the solution annealed and aged yield strength value of 268 KSI. Consequently, the cold work tensile data were quite disappointing. No explanation can be offered at this time as to why the properties were low, considering the amount of cold work induced. The reasons for this behavior are now under study. As shown in Figure 200 where longitudinal yield strength as a function of cold work and the Larson-Miller Parameter "P" are plotted, the maximum yield strength was achieved by a 40% cold work level at a Larson-Miller Parameter equivalent to 900°F/1 hour.

3.2.2 Effect of Cold Work on Fracture Toughness Parameters

The effects of cold work level and maraging parameters on longitudinal and transverse fracture toughness are presented in Tables 125 and 126. The longitudinal and transverse fracture toughness parameter [illegible] plotted as a function of cold work and maraging time at 900°F, [illegible] Figure 201.

Longitudinal K_c values are excellent regardless of cold work level and maraging time. Values range from 158 KSI $\sqrt{in.}$ to 198 KSI $\sqrt{in.}$ Both the peak and the lowest K_c values were obtained from the 50% cold worked material.

Transverse K_c properties are half the longitudinal K_c values, ranging from 70 KSI $\sqrt{in.}$ to 86 KSI $\sqrt{in.}$ The 900°F/10 hour marage produced slightly higher transverse K_c values than the 900°F/3 hour marage. Transverse properties were rather consistent with increasing cold work.

3.3 Miscellaneous Properties

3.3.1 Elevated Temperature Properties

Figure 202 presents the plot of tensile strength as a function of test temperatures from room temperature to 1000°F. Specimens were heat treated as follows:

Soln:	1450°F/½ hour
Ausage:	1200°F/4 hours
Refrigerate:	-110°F/16 hours
Marage:	900°F/3 hours

Ultimate and yield strength fell sharply from 250°F (276 KSI and 249 KSI, respectively) to 1000°F (143 KSI and 90 KSI, respectively). Ductility increased correspondingly from an R.A. of 40% to 61%.

3.3.2 Heat Treat Response of a Thick Section

The heat treat response of a 4½" x 4½" x 5½" billet was measured by removing surface and center bar specimens after heat treating as follows:

Solution: 1450°F/1 hr/inch section
1200°F/4 hr/inch section
Refrig: -110°F/16 hrs/inch section
Marage: 900°F/3 hrs/inch section

Table 127 reports the results of this study. Very poor ductility caused by incomplete billet homogenization was the probable cause of poor specimen performance. In the same manner as the 20% nickel alloy, the 25% nickel appears to require very thorough conditioning in order to reach anticipated strength and ductility in heavy section sizes.

3.3.3 Effect of Forging Reduction on Tensile Properties

The effects of forging reduction on the properties of forgings were determined similarly to the studies previously discussed for the preceding alloys. The results on the 25% nickel alloy are reported in Table 128. Figures 203 through 206 present the tensile properties as a function of forging reduction and specimen location and direction.

Forging properties are, in general, poor. The initial billet properties are superior to those representing all forging reductions. Ductility values were quite poor also.

The spread in yield to ultimate tensile strength (approx. 50 KSI) indicates that the billet and subsequent forgings did not possess homogeneous structures.

3.3.4 Fatigue Properties

The smooth and notched bar fatigue endurance strengths for solutioned and aged, 25% nickel alloy were determined from the S-N curves shown in Figure 207. The smooth bar endurance strength (10^8 cycles) was determined to be 65,000 psi. Notched bar endurance strength was 50,000 psi.

Figure 208 presents the smooth bar S-N curve for 30% cold worked 25% nickel alloy. The endurance strength of 30% cold worked material was 77,000 psi.

3.3.5 Impact Properties

The room temperature and cryogenic Charpy impact strengths for solution and aged and cold worked and maraged 25% nickel alloy are presented in Figures 209 and 210, respectively. Impact strength of material solutioned at 1450°F/½ hr, ausaged 1200°F/4 hrs, refrigerated -110°F/16 hrs. and maraged 900°F/3 hrs was a meager 5 ft-lbs at room temperature and a relatively comparable 3 ft-lbs at -300°F.

Cold worked 30%, refrigerated -110°F/16 hr, maraged 900°F/1 hr material yielded room temperature impact strength of 19 ft-lbs. At -300°F a value of 12.5 ft-lbs was obtained. Cold worked 40%, refrigerated -110°F/16 hours, maraged 900°F/1 hr material exhibited a room temperature impact strength of 15 ft-lbs which fell to 10 ft-lbs at -300°F.

3.4 Summary Discussion

A general comparison of fracture toughness parameters (Table 129). for solutioned and maraged versus cold worked and maraged 25% nickel alloy, reveals the cold worked material to exhibit superior K_c values (approx. 180 versus 120 KSI $\sqrt{in}$) at approximately the same yield strength level (235 to 250 KSI) as shown in Figure 211.

The results obtained for the 25% nickel heat were considered poor since, (as concluded for the 20% nickel heat) the 25% nickel alloy is known to be capable of superior properties than those obtained.

The microstructure of the 25% nickel alloy produced by the various heat treat cycles is shown in Figure 212. The structure after solutioning at 1500°F/1 hr is equally divided between austenite and martensite. After the 1300°F ausage, the photomicrographs show excellent

definition of a duplex structure with the granular structure of $Ni_3(Al,Ti)$. Theoretically, the ausaging treatment should cause nearly complete transformation to martensite on cooling. However, as shown in the electron micrographs, substantial amounts of austenite were retained. After refrigeration at -110°F/16 hours and maraging 900°F/3 hours, a complete transformation to martensite occurred.

3.5 Weld Properties

Presented in the following sections are hardness, and tensile properties for the 25% nickel alloy welded in both solution heat treated and cold worked conditions. The welding filler materials investigated are also evaluated on the basis of fracture toughness.

3.5.1 Hardness Properties

Weld Zone

Presented in Table 130 are vertical hardness traverses taken along the weld centerlines. Welds produced using the 18% nickel (250 KSI) and all three modified 20% nickel wires were evaluated.

The data plotted in Figure 213 show that after refrigeration and maraging the fusion pass area of welds and the filler wire deposit areas are almost equal in hardness (51-53 Rc) in all cases examined. The various filler wire deposits showed no appreciable difference in aged hardness (Figure 213). A similar behavior was observed in longitudinal weld hardnesses taken between the weld centerline and the weld-base metal interface, Table 129.

Heat-Affected Zone

Longitudinal hardness surveys taken in weld heat-affected zones between the weld-base metal interface and unaffected base material are presented in Table 131. These data are represented graphically in Figures 214 and 215.

Wide scatter was observed in hardness data taken in four surveys in the heat-affected zone of solution heat treated sheet (Table 131). This scatter, indicated by a hardness band in Figure 214, is probably associated with a variation in the location of the area subjected to ausaging temperatures (1200-1400°F). In general, the maximum degree of ausaging experienced was in the area about 0.200" from the weld heat affected zone, as indicated by the as-welded band in Figure 214. Since hardness increased only 5 to 10 R_c, it appeared that only partial ausaging was experienced during welding. Normal ausaging response for unwelded sheet results in a hardness increase of

approximately 20-25 R_c. Refrigeration and maraging at 850°F/4 hours equalized hardness across the heat-affected zone at a level of about 52 to 53 R_c (Figure 214). The wide scatter observed in the as-welded condition was not apparent after maraging.

A typical hardness survey across a weld heat affected zone in cold worked sheet is shown in Figure 215. The area adjacent to the weld interface was completely resolutioned to a hardness of less than 15 R_c An ausaging effect similar to that noted in solution heat treated sheet was also observed in the cold worked sheet. (Figure 215). Hardness in this area was about 40 R_c as compared to 35 R_c in unaffected material. Refrigeration and maraging increased hardness in the resolutioned zone to 52 R_c and to 55 R_c in unaffected base material. (Figure 215).

3.5.2 Tensile Properties

The same procedures used for evaluation of welding filler materials on 20% nickel alloy (Section 2.6.2) were followed in this section.

Solution Heat Treated Base Material (0.140" sheet)

Transverse weld tensile test results comparing various filler compositions are shown in Table 132 and Figure 216. Preliminary evaluations were made on welds subjected to the following heat treatment cycle: 1300°F/4 hrs + Refrigeration at -110°F/16 hrs + 850°F/4 hrs. In these tests, welds made using the modified 20% nickel (7C-059) and 20% nickel (7C-060) filler wires demonstrated the highest yield strength joint efficiencies, 101% (264 KSI) and 98% (256 KSI), respectively. (Table 132). A high level of yield strength (251 KSI) was also noted in welds made with the 18% nickel (250 KSI) alloy, despite lengthy exposure to 1300°F in ausaging, a treatment reported to be damaging to maraging response of the 18% nickel Group I Alloys.

Subsequent tests were made using a heat treatment known to provide a good balance of strength and toughness in unwelded sheet. This treatment, 1200°F/4 hrs + Refrigeration + 900°F/3 hrs proved damaging to weld properties. (Table 132 and Figure 216). Failures located partially in the heat affected zone were experienced in some specimens, and resulted in reduced weld strength and reduction in area. (Table 132). This behavior was independent of filler wire used. In all cases, weld yield strengths were at least 25 KSI lower than those obtained in preliminary tensile tests (Figure 216). As shown in Table 132, only welds made with the 20% nickel molybdenum containing wire (7C-060) failed to show a loss in ductility.

Solution Heat Treated Base Material (0.070" sheet)

Transverse tensile properties of welds in 0.070" sheet are presented in Table 108 and Figure 216. All test specimens were heat treated as follows: 1200°F/4 hrs + Refrigeration + 900°F/3 hrs. Brittle heat-affected zone failures were experienced in practically all specimens tested, which resulted in extremely poor tensile strengths of 183 to 207 KSI (Table 108). Unlike similar behavior noted in 20% nickel welds in 0.070" thick sheet (Table 108) and 25% nickel welds in 0.140 sheet (Table 108), fractures in these specimens were located entirely in the weld heat-affected zone.

30% Cold Worked Base Material (0.140" sheet)

Results of transverse tensile tests made on welds produced in cold worked sheet are presented in Table 133 and Figure 217. All specimens were refrigerated at -110°F for 16 hrs and maraged at 900°F for 1 hour. Only the 18% nickel (300 KSI) and the two molybdenum containing 20% nickel alloys were evaluated. None of these wires deposited welds which responded favorably to refrigeration and maraging heat treatment only. In general, yield strength properties were exceedingly low, varying from 183 KSI (80% joint efficiency) to 197 KSI (86% joint efficiency). (Table 133). Maximum properties were obtained in welds made with both the 18% nickel (300 KSI) and the modified 20% nickel, molybdenum containing (7C-059) wire.

3.5.3 Fracture Toughness

Weld fracture toughness properties for the filler materials evaluated are presented in Table 134 and Figure 218. All specimens were given a heat treatment of 1200°F/4 hrs + Refrigeration at -110°F/16 hrs + 900°F/3 hrs. Using this heat treatment, all welds tested exhibited reasonably good average fracture toughness properties with the exception of that made with the molybdenum-free, modified 20% nickel wire (Table 134). It should be noted that calculation of weld fracture toughness values were based on weld joint yield strengths obtained for the same heat treatment used in fracture toughness tests. Although partial heat affected zone tensile failures were experienced using these heat treatments (Table 134), these data represented the best available baseline for calculation of weld fracture toughness.

As shown in Figure 218, maximum toughness (K_c) of 136 to 190 KSI $\sqrt{in}$ was exhibited by the 20% nickel, molybdenum containing wire (7C-060). Welds made with both 18% nickel alloy wires showed comparable toughness. (Figure 218). This was based, however, on a lower yield strength level of 216 KSI as opposed to 228 KSI for the 20% nickel wire weld (Table 134). Weld fracture toughness compared favorably with that reported for similarly heat treated 25% nickel sheet in

in Tables 118 and 119 (K_c longitudinal -160 to 216 KSI $\sqrt{in.}$, K_c transverse -102 to 140 KSI $\sqrt{in.}$).

3.5.4 Summary

On the basis of weld tests made in this investigation, the 25% nickel alloy exhibited lowest level of weldability of the four nickel-iron alloys evaluated.

A sensitivity to heat-affected-zone embrittlement was observed in welds made in both 0.070" and 0.140" thick solution heat treated sheet using certain heat treatments. Test results demonstrated that of the two heat treatments evaluated, that which is known to give the best balance of properties in base materials caused embrittlement in the weld-heat-affected zone.

All of the filler wires investigated were found to deposit sound, defect-free welds and heat affected zones in 25% nickel alloy sheet in both solution heat treated and cold worked conditions. Welds were produced using conventional welding procedures without benefit of a "preheat-interpass-postheat" weld thermal cycle. Both weld and heat-affected zone demonstrated freedom from embrittlement prior to heat treatment as determined by bend tests.

Welding filler materials are compared on the basis of strength, ductility, and toughness in Table 135 and Figure 219. Tensile data obtained in preliminary tests are also included in this summary table and figure for comparison purposes, since the heat treatment preferred for base material and used in final tests caused deterioration in weld properties.

As shown in Figure 219, the molybdenum containing 20% nickel wires (7C-059 and 7C-060) deposited welds of maximum strength in solution heat treated sheet using either heat treatment. Where maximum weld fracture toughness is desired, the 7C-060 wire is superior, but at a slightly reduced yield strength level (Table 135).

Exposure of 18% nickel alloy weld deposits to a 1300°F treatment did not cause a pronounced loss in maraging response due to austenite stabilization, which might be expected (Table 135). The effect of the 1200°F treatment on stabilization was not determined since tensile failures occurred in the weld heat-affected zone (Table 132).

Welded cold worked material exhibited prohibitively low yield strength joint efficiencies (Figure 219). This behavior is believed to be associated with the exclusion of an ausaging step, which was dictated by unwelded sheet fracture toughness considerations.

EFFECT OF SOLUTIONING PARAMETERS ON THE HARDNESS
OF SOLUTION ANNEALED 25% NICKEL ALLOY

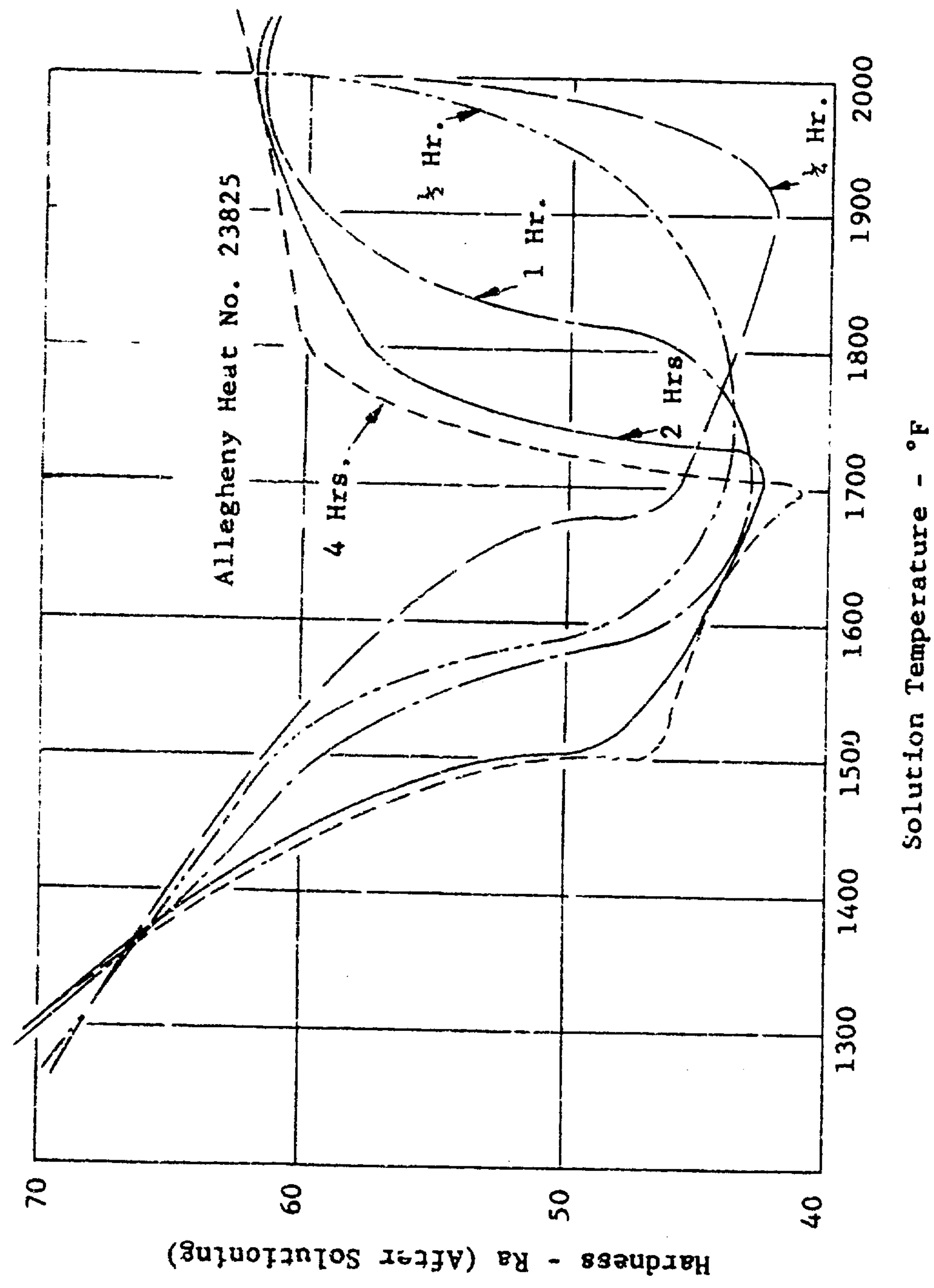


Figure 188

EFFECT OF SOLUTION TEMPERATURE AND TIME ON THE "AS QUENCHED" (AIR COOLED) HARDNESS OF 25% NICKEL ALLOY*

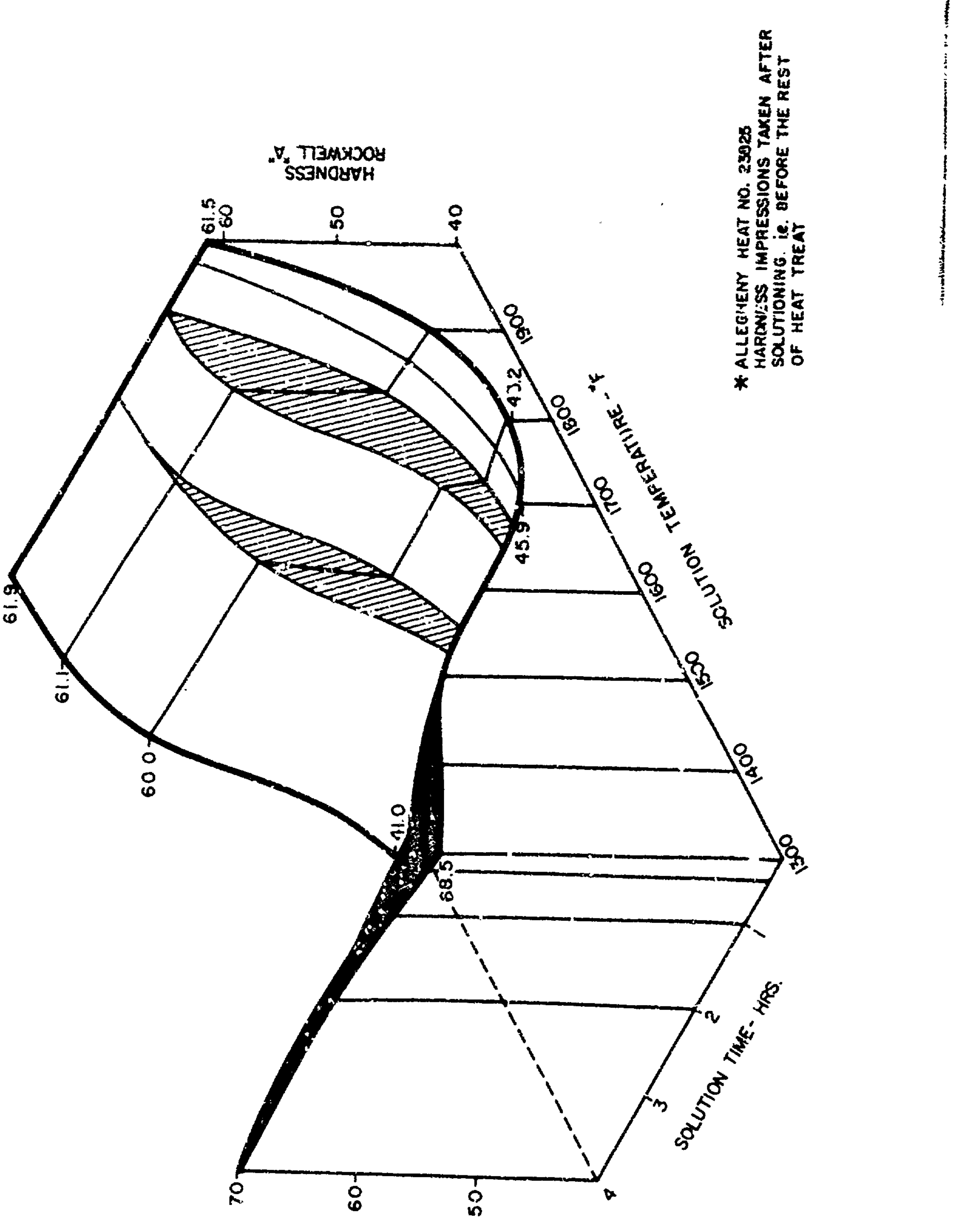


Figure 189

EFFECT OF AUSAGING PARAMETERS ON THE HARDNESS OF SOLUTION ANNEALED 25% NICKEL ALLOY

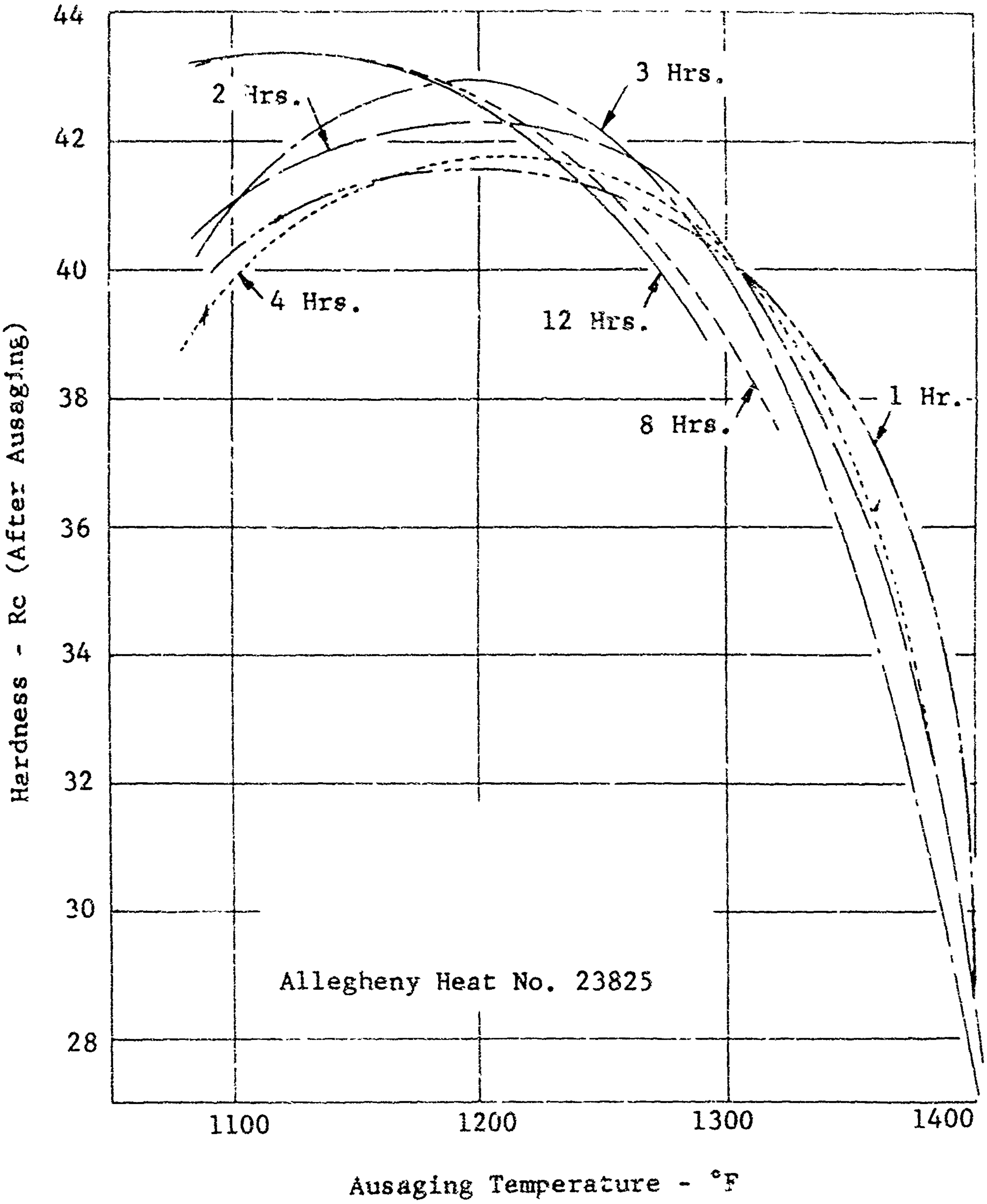


Figure 190

EFFECT OF MARAGING PARAMETERS ON THE HARDNESS OF
SOLUTION ANNEALED 25% NICKEL ALLOY

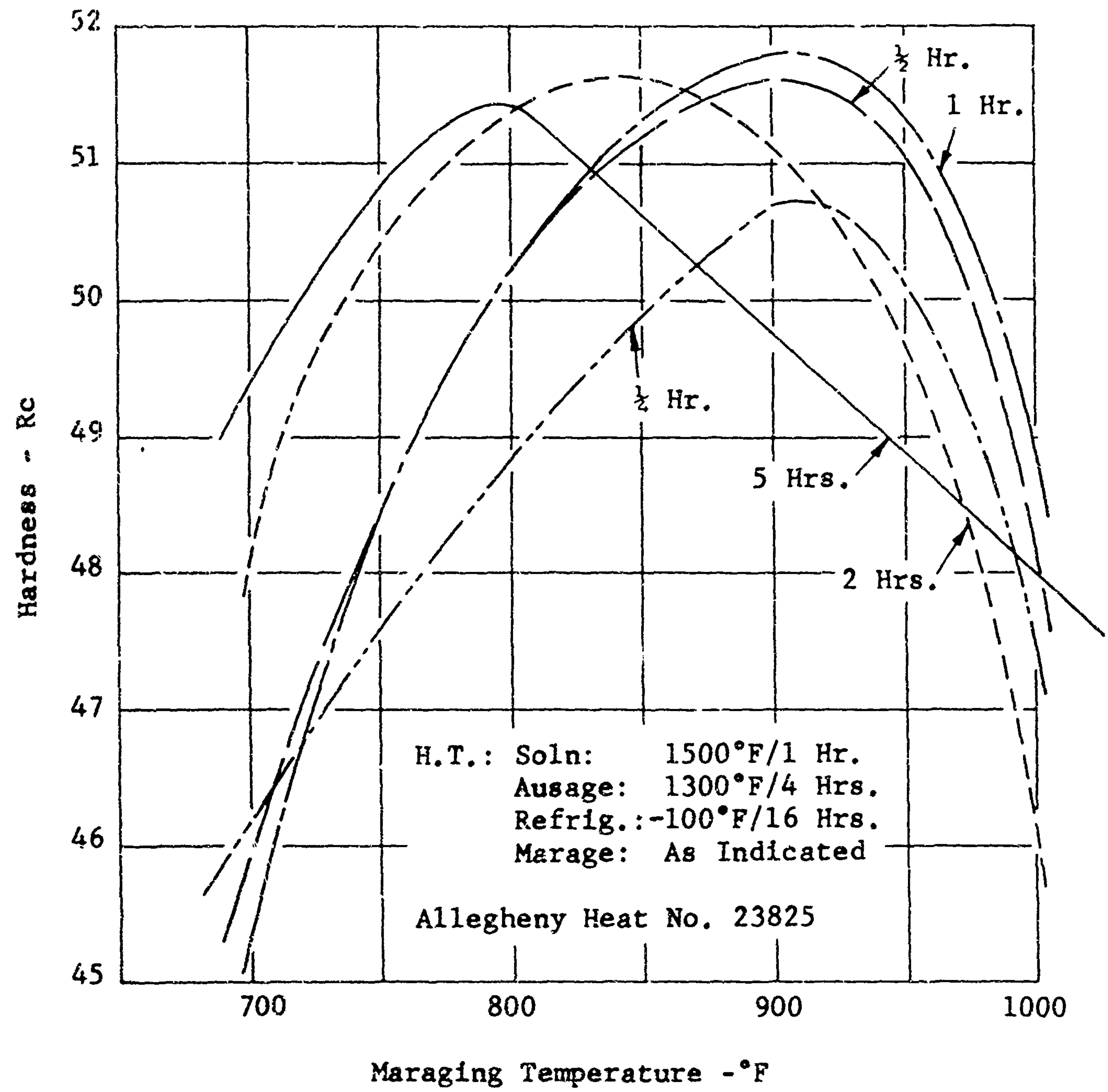


Figure 191

EFFECT OF SOLUTION TEMPERATURE ON THE
LONGITUDINAL YIELD STRENGTH OF 25% NICKEL ALLOY

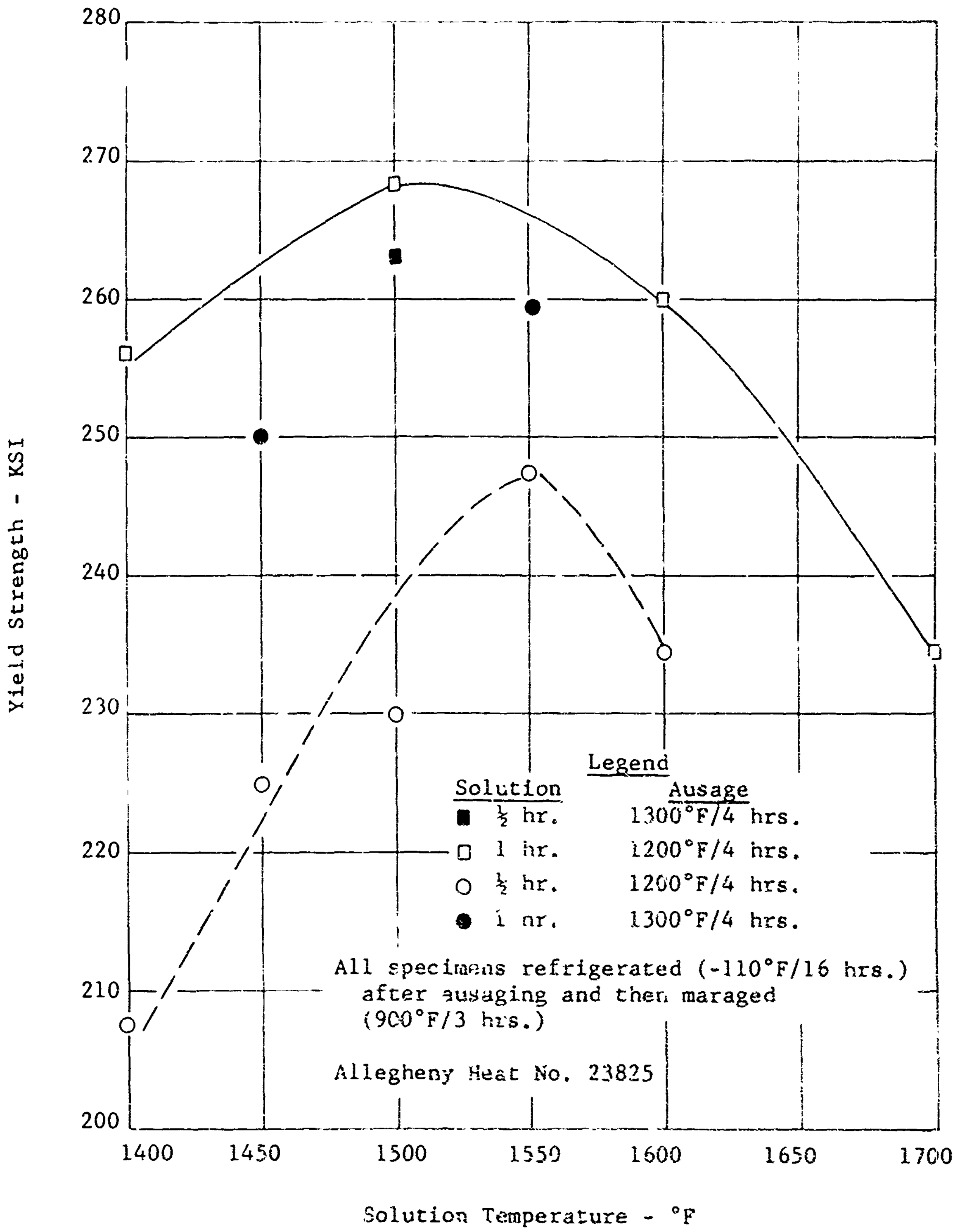
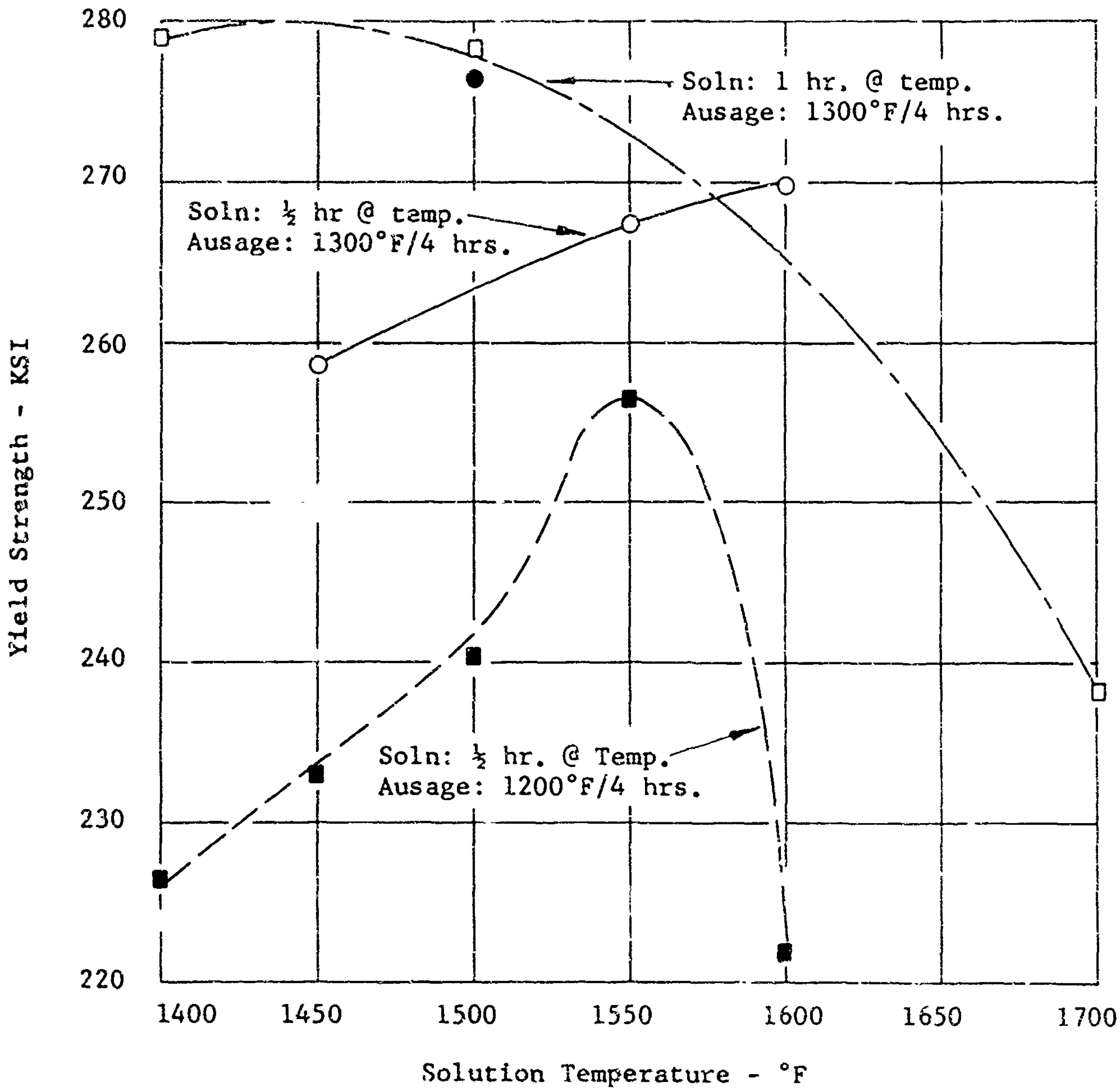


Figure 192

EFFECT OF SOLUTION TEMPERATURE ON THE TRANSVERSE YIELD STRENGTH OF 25% NI ALLOY



All specimens refrigerated (-110°F/16 hrs.) after ausaging and maraged (900°F/3 hrs.)

Allegheny Heat No. 23825

LEGEND

	Solution	Marage
■	½ hr.	1200°F/4 hrs.
□	1 hr.	1300°F/4 hrs.
○	½ hr.	1300°F/4 hrs.
●	1 hr	1200°F/4 hrs.

Figure 193

EFFECT OF SOLUTIONING TEMPERATURE
ON THE FRACTURE TOUGHNESS OF 25% Ni ALLOY

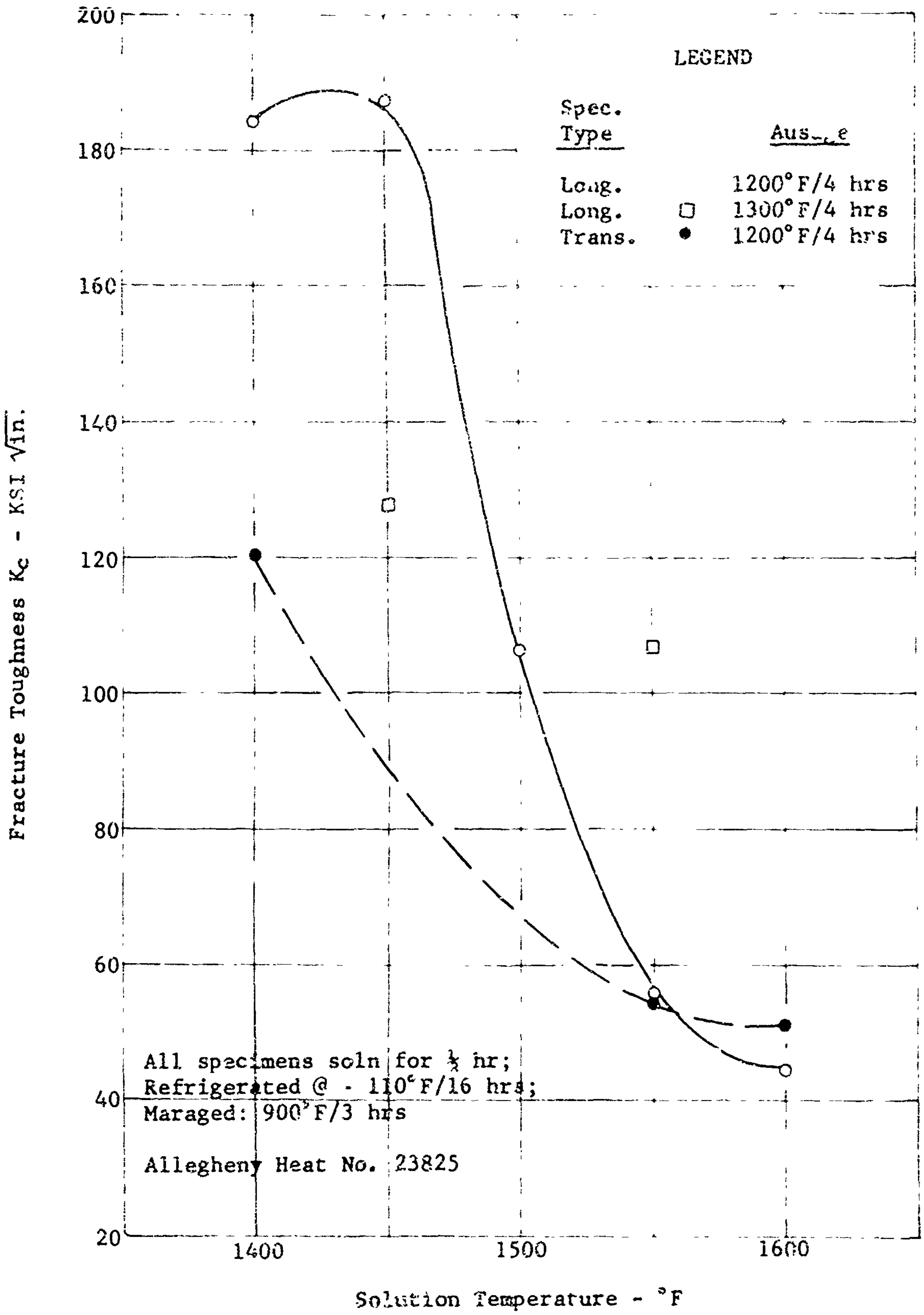


Figure 194

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON
THE LONGITUDINAL YIELD STRENGTH OF
UNREFRIG. 25% Ni ALLOY

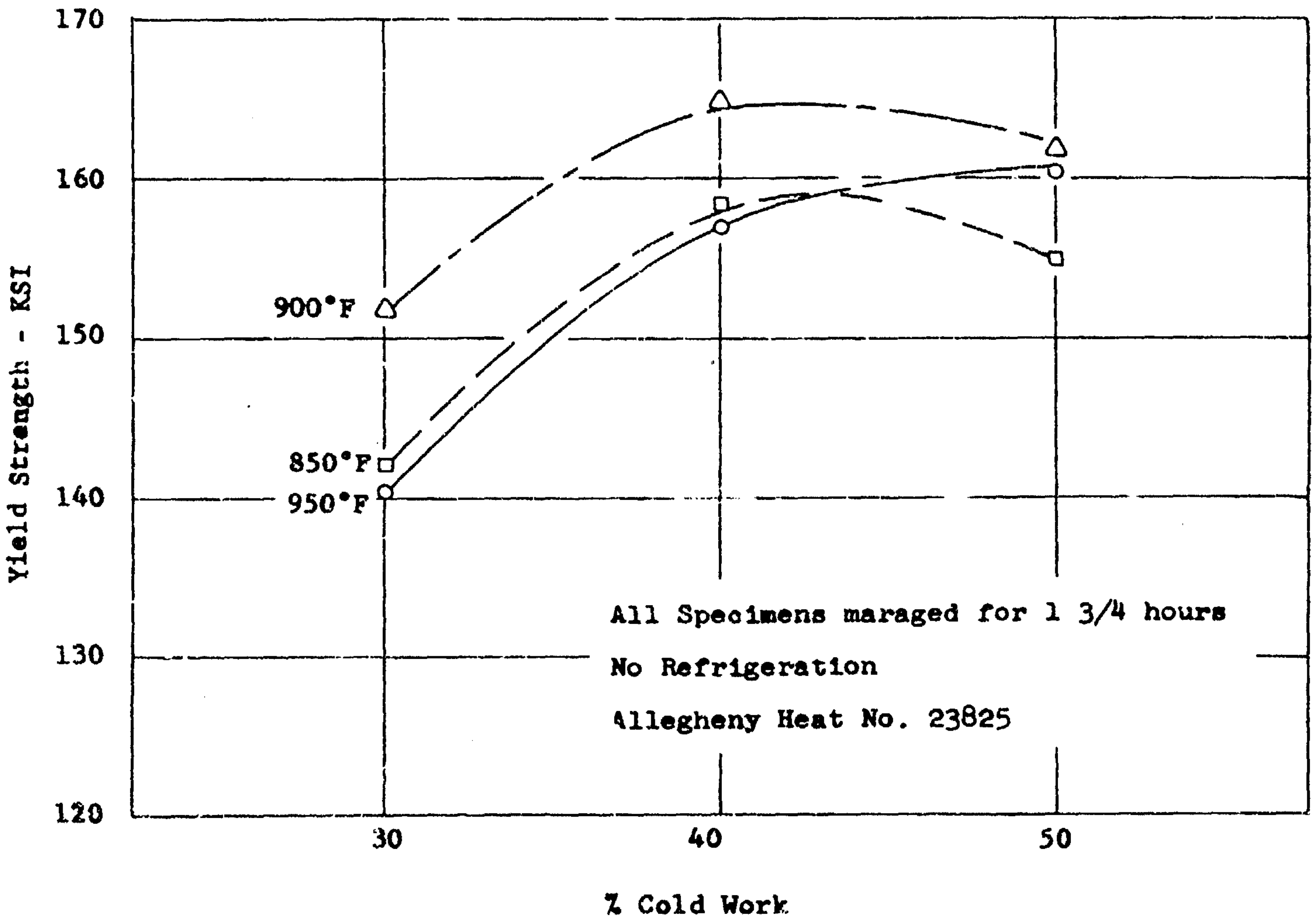


Figure 195

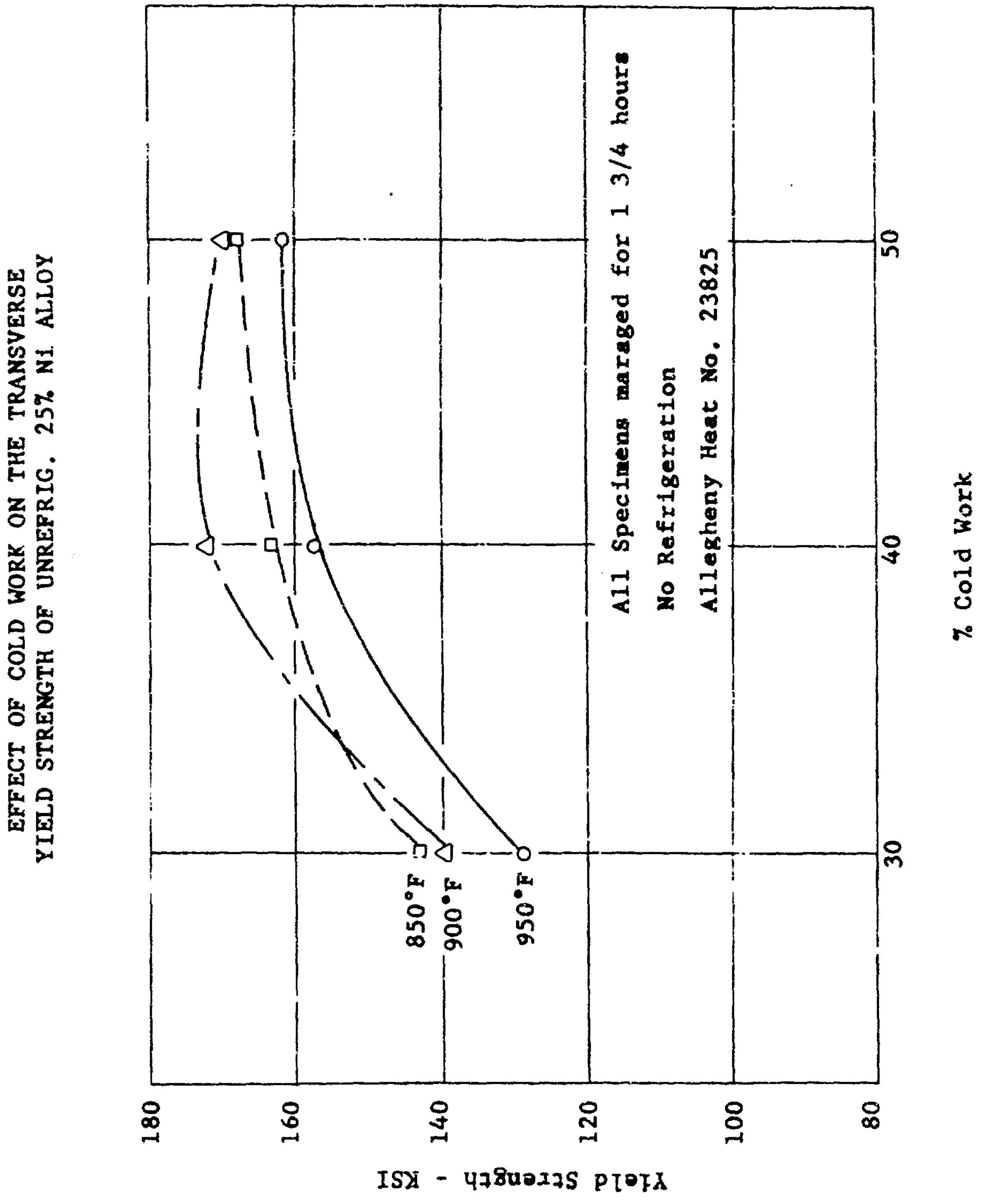

EFFECT OF COLD WORK ON THE TRANSVERSE
YIELD STRENGTH OF UNREFRIG. 25% Ni ALLOY
All Specimens maraged for 1 3/4 hours
No Refrigeration
Allegheny Heat No. 23825
850°F
900°F
950°F
180
160
140
120
100
80
Yield Strength - KSI
30
40
50
% Cold Work

Figure 196

ISOCHRONAL TRANSFORMATIONS OF RETAINED AUSTENITE IN THE COLD WORKED 25% NICKEL ALLOY

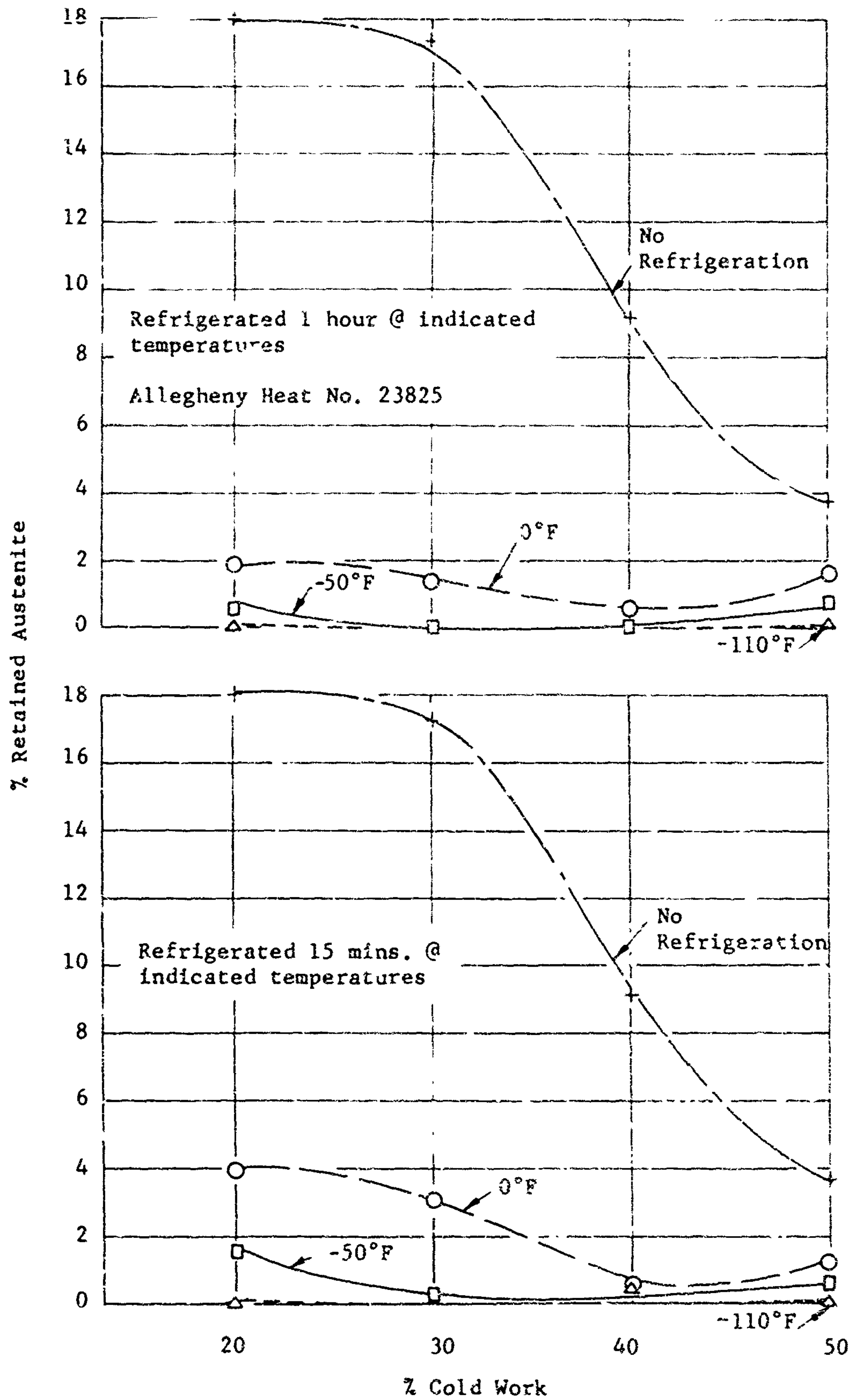


Figure 197

3874

EFFECT OF COLD WORK AND MARAGING TIME ON
THE LONGITUDINAL YIELD STRENGTH OF 25% NI ALLOY

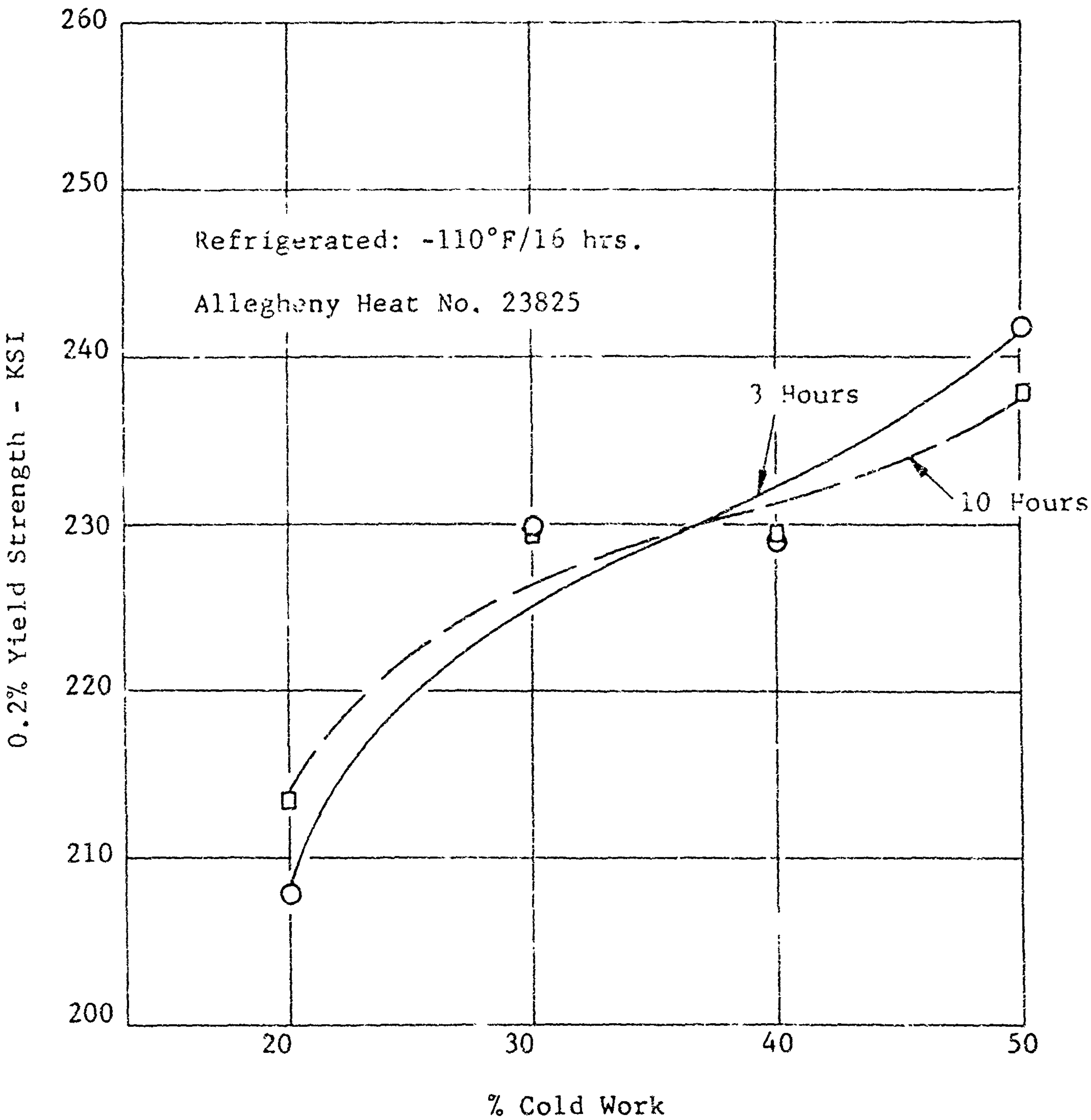


Figure 198

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON THE TRANSVERSE YIELD STRENGTH OF REFRIGERATED 25% Ni ALLOY

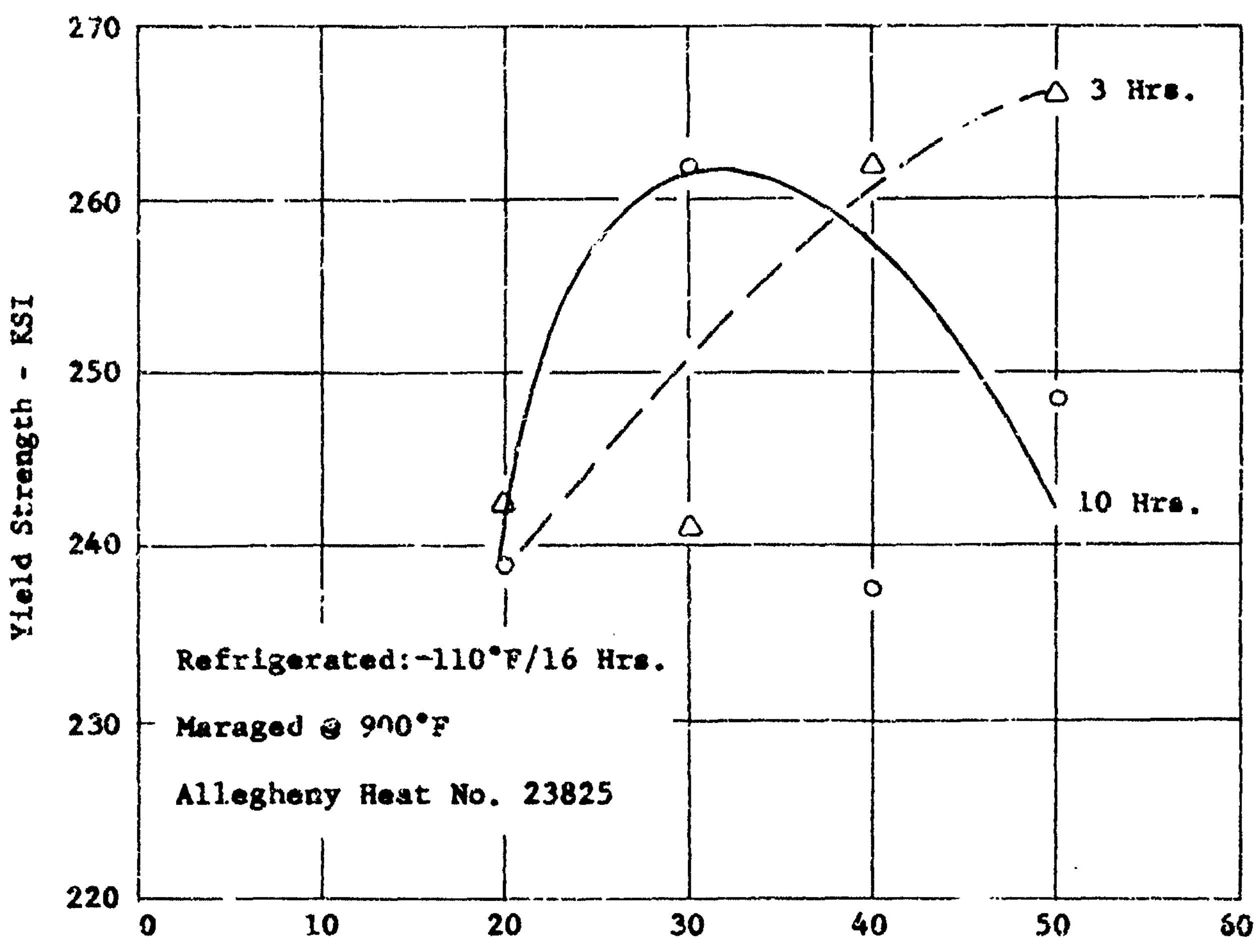


FIG 199

420

~~Figure~~ 199

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON LONGITUDINAL YIELD STRENGTH OF 25% NICKEL ALLOY

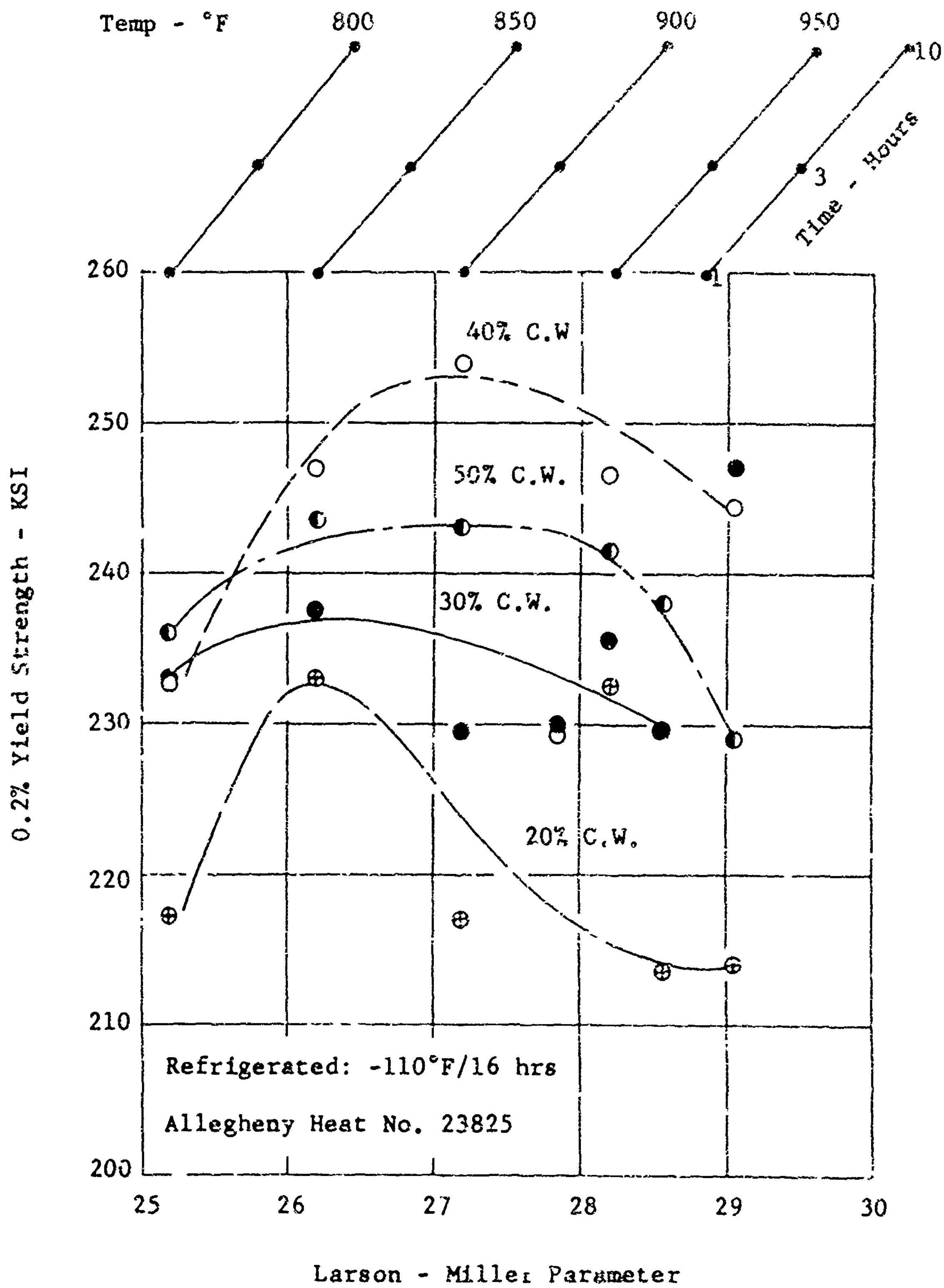


Figure 200

4156

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON THE FRACTURE TOUGHNESS OF 25% Ni ALLOY*

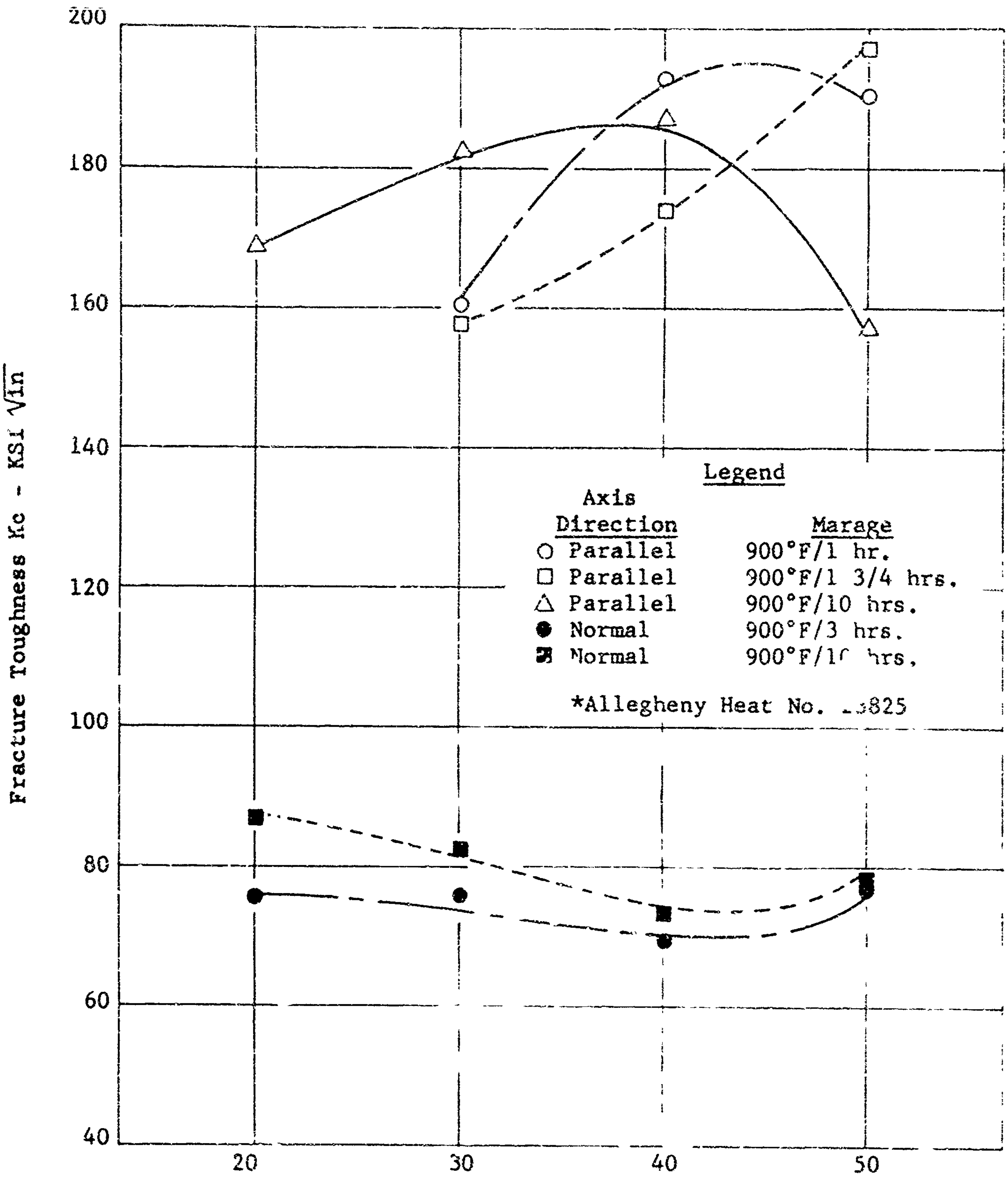


Figure 201

(16)

ELEVATED TEMPERATURE TENSILE PROPERTIES OF
SOLUTION ANNEALED 25% NICKEL ALLOY

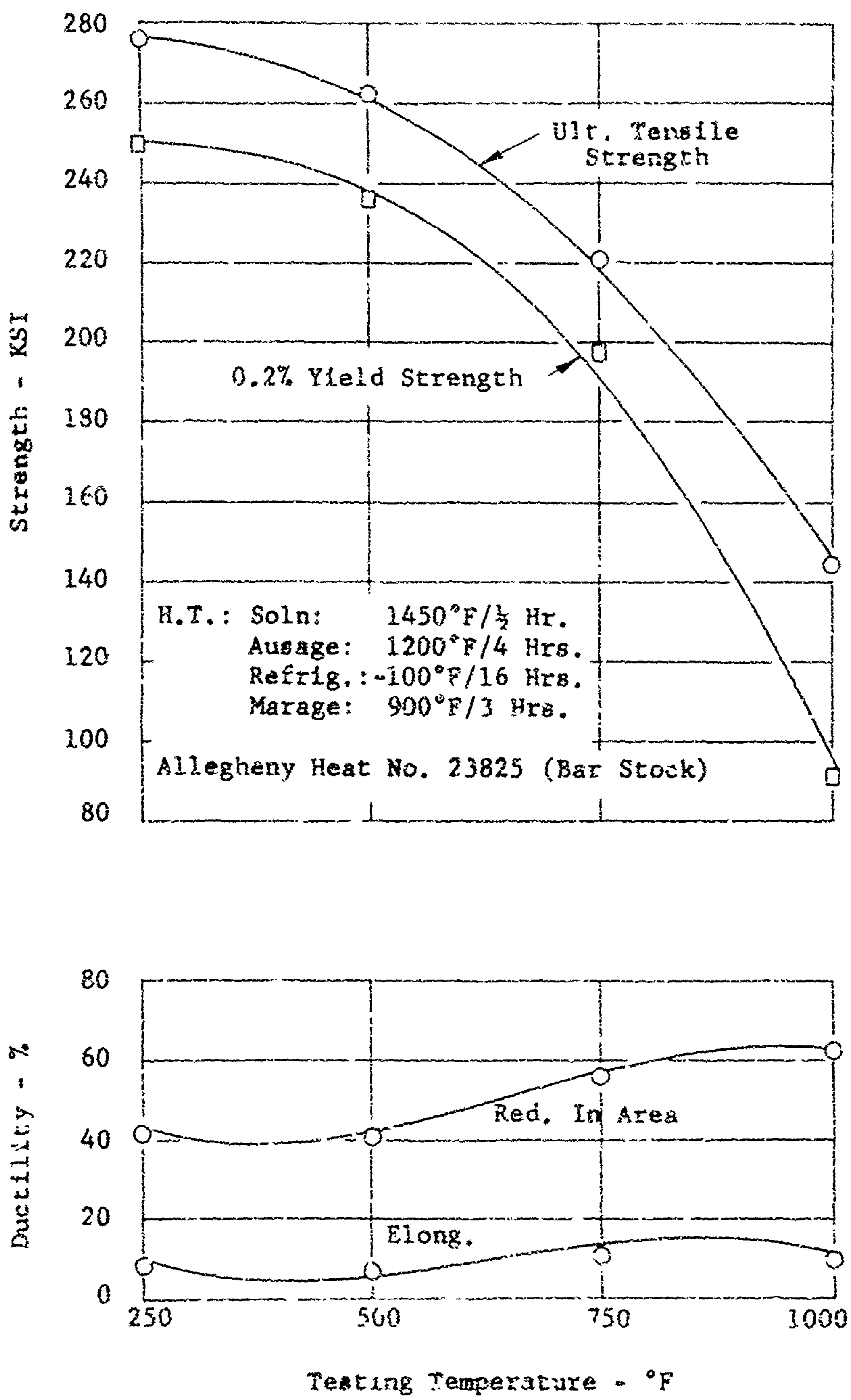


Figure 202

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 25% NICKEL ALLOY

LOCATION: VERTICAL-CENTER

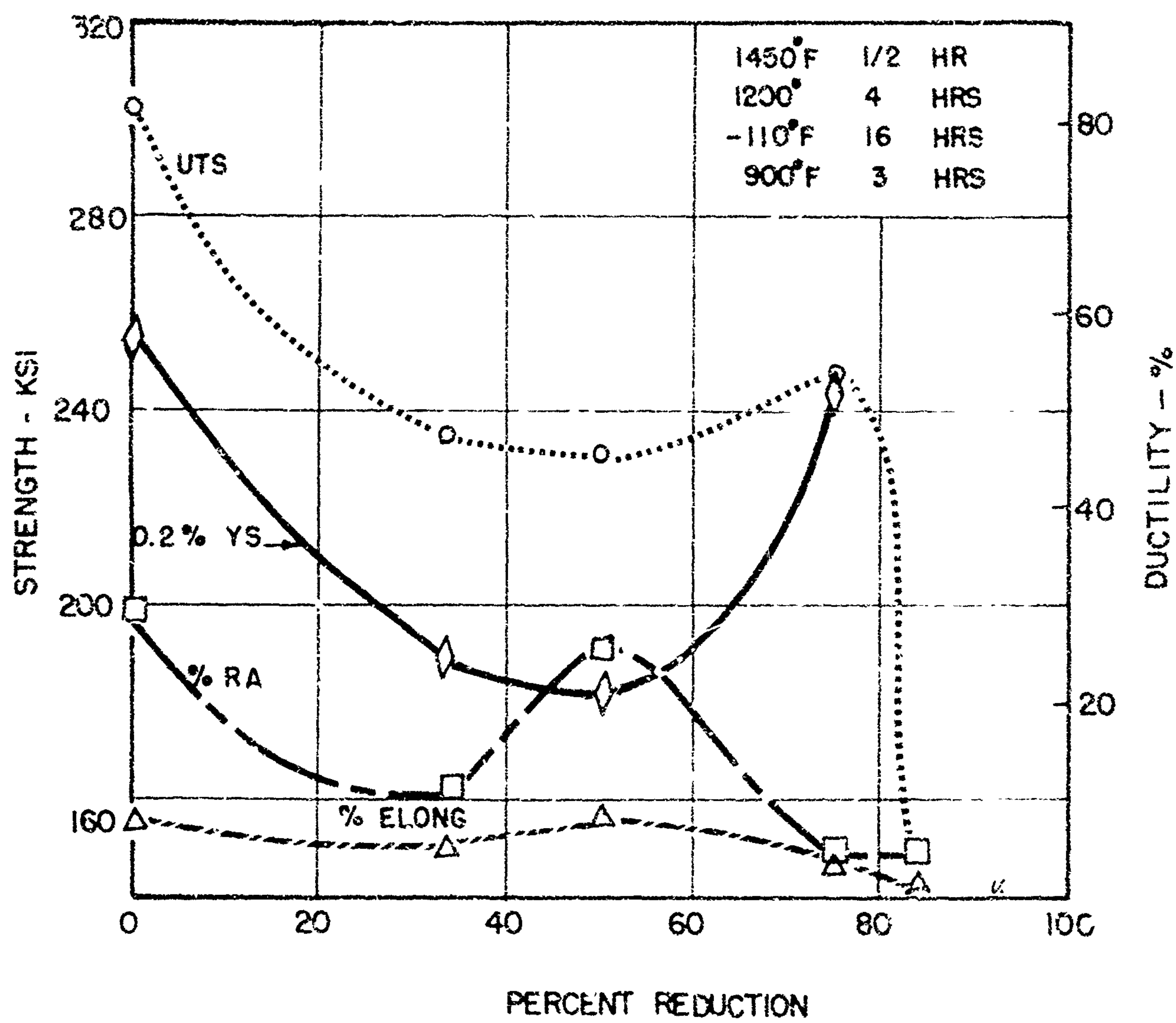


Figure 203

5326

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 25% NICKEL ALLOY

LOCATION: VERTICAL-EDGE

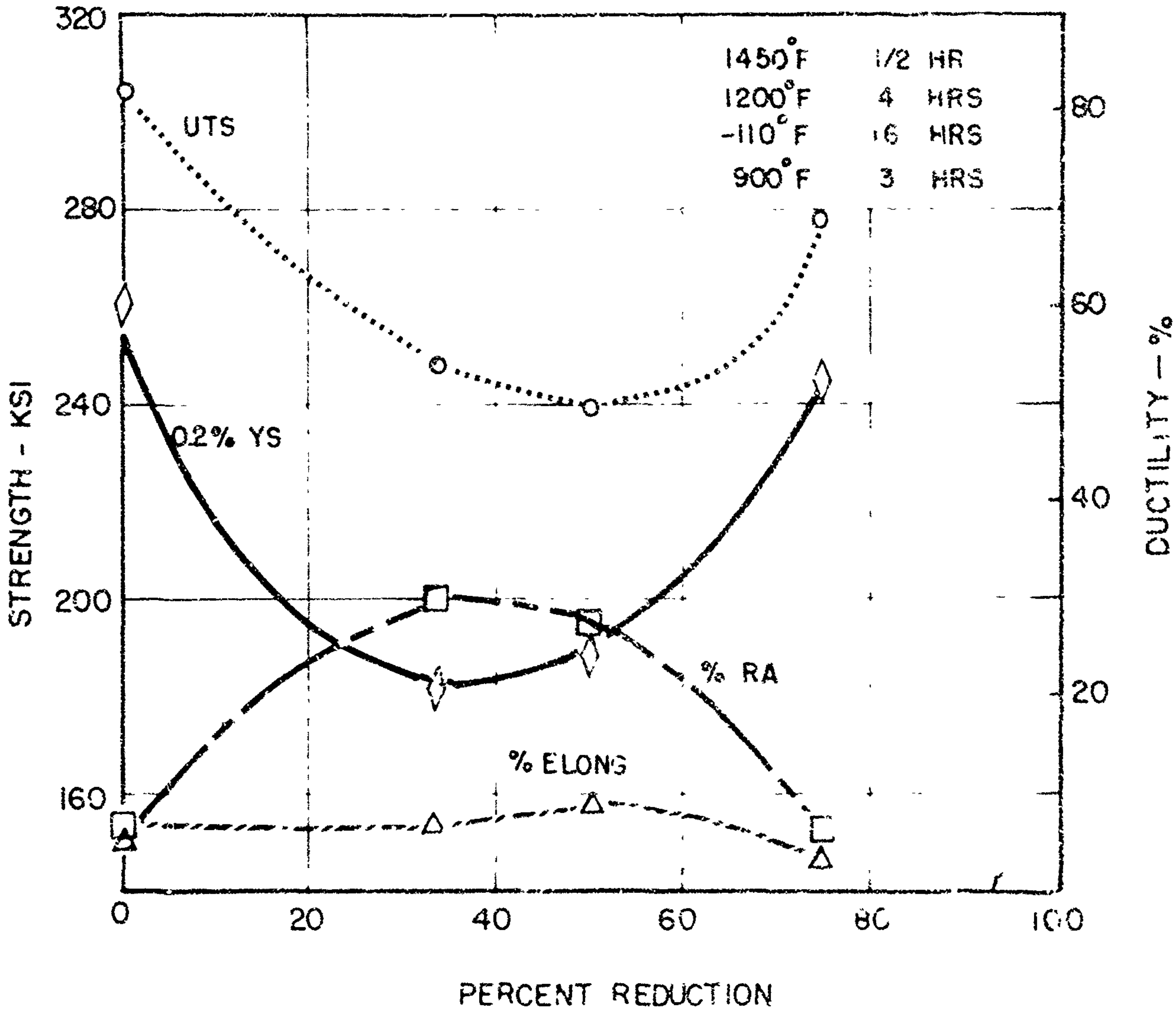


Figure 204

EFFECT OF FORGING REDUCING ON THE PROPERTIES
OF 25% NICKEL ALLOY

LOCATION: HORIZONTAL-CENTER

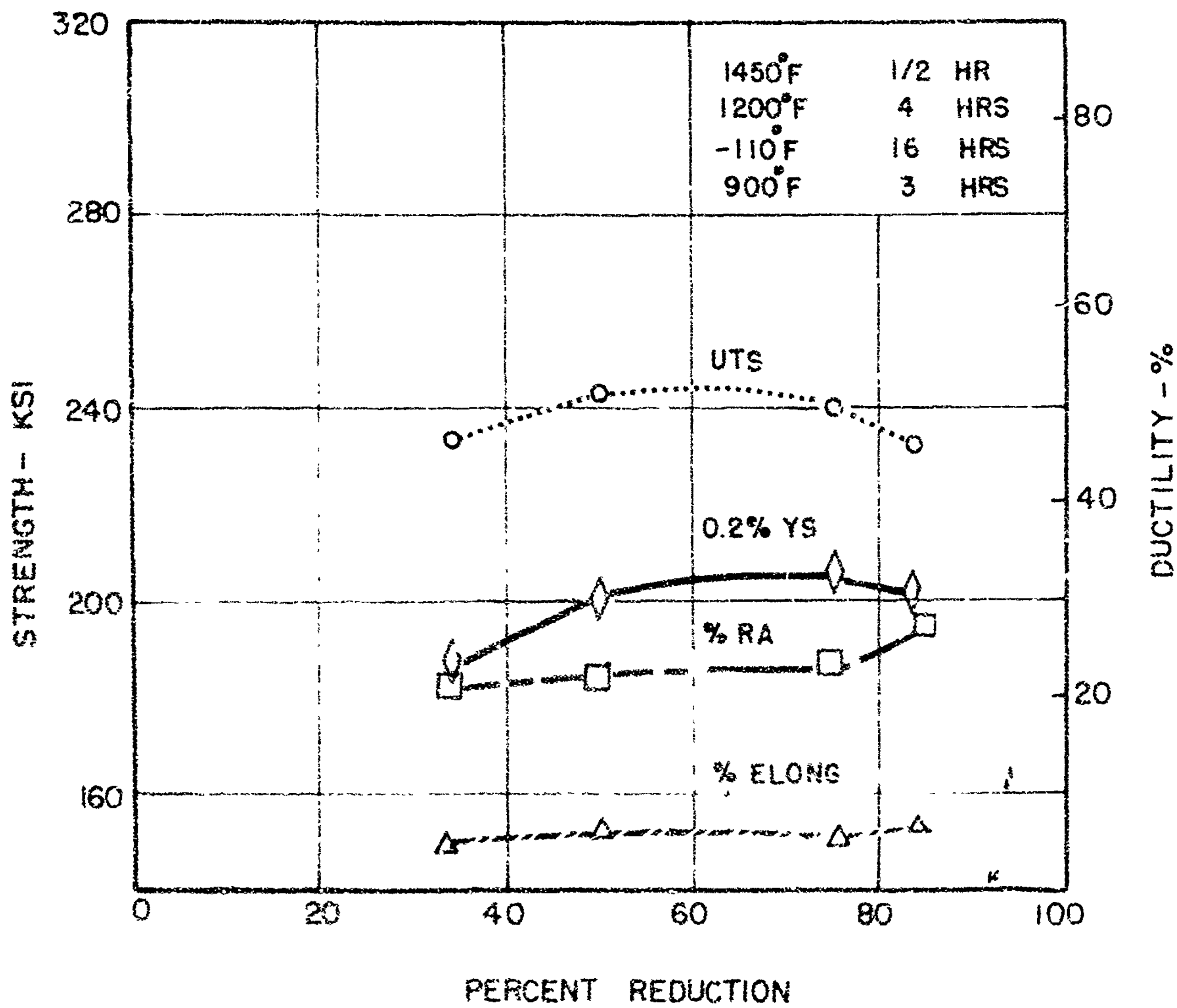


Figure 205

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 25% NICKEL ALLOY

LOCATION: HORIZONTAL - EDGE

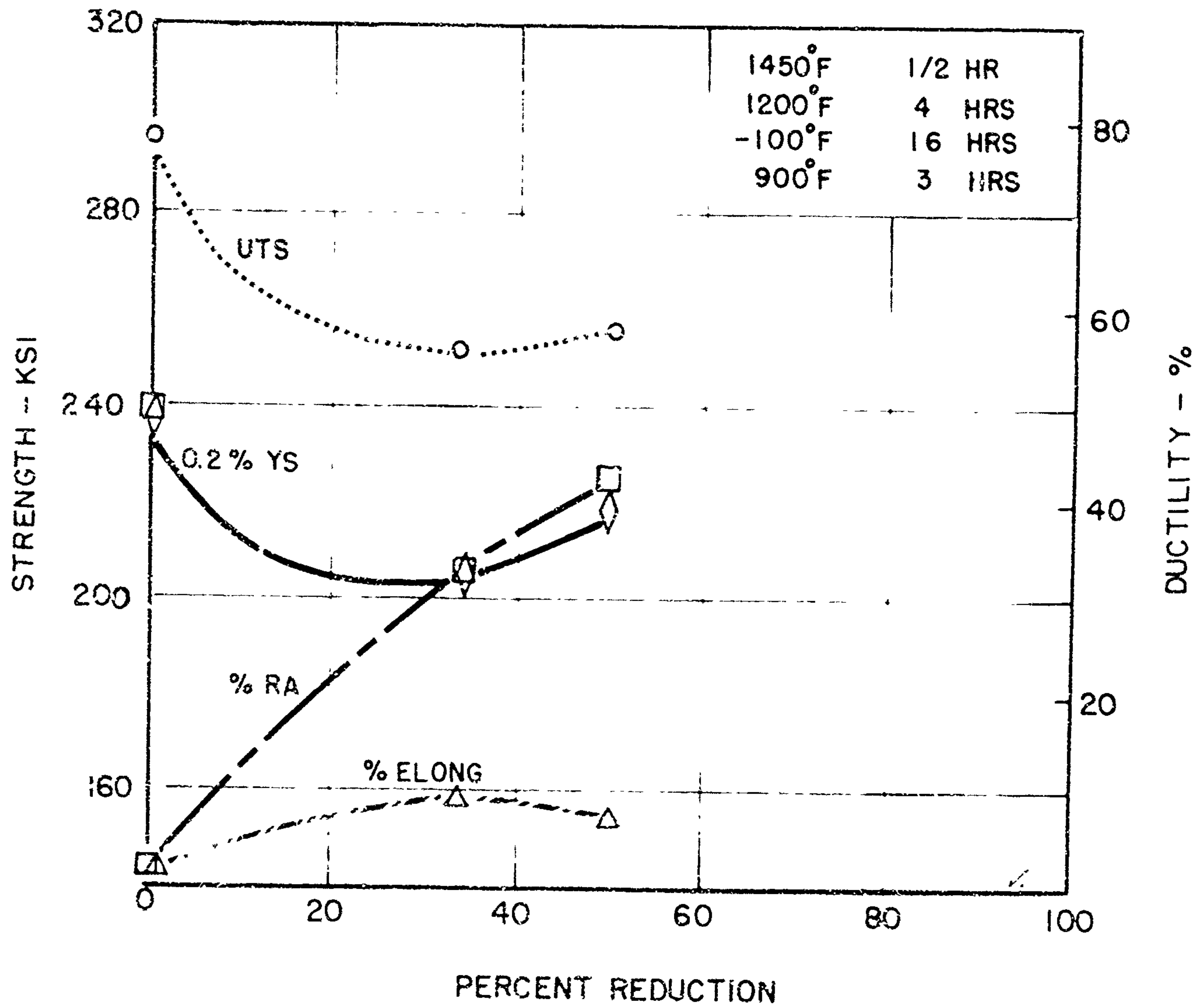


Figure 206

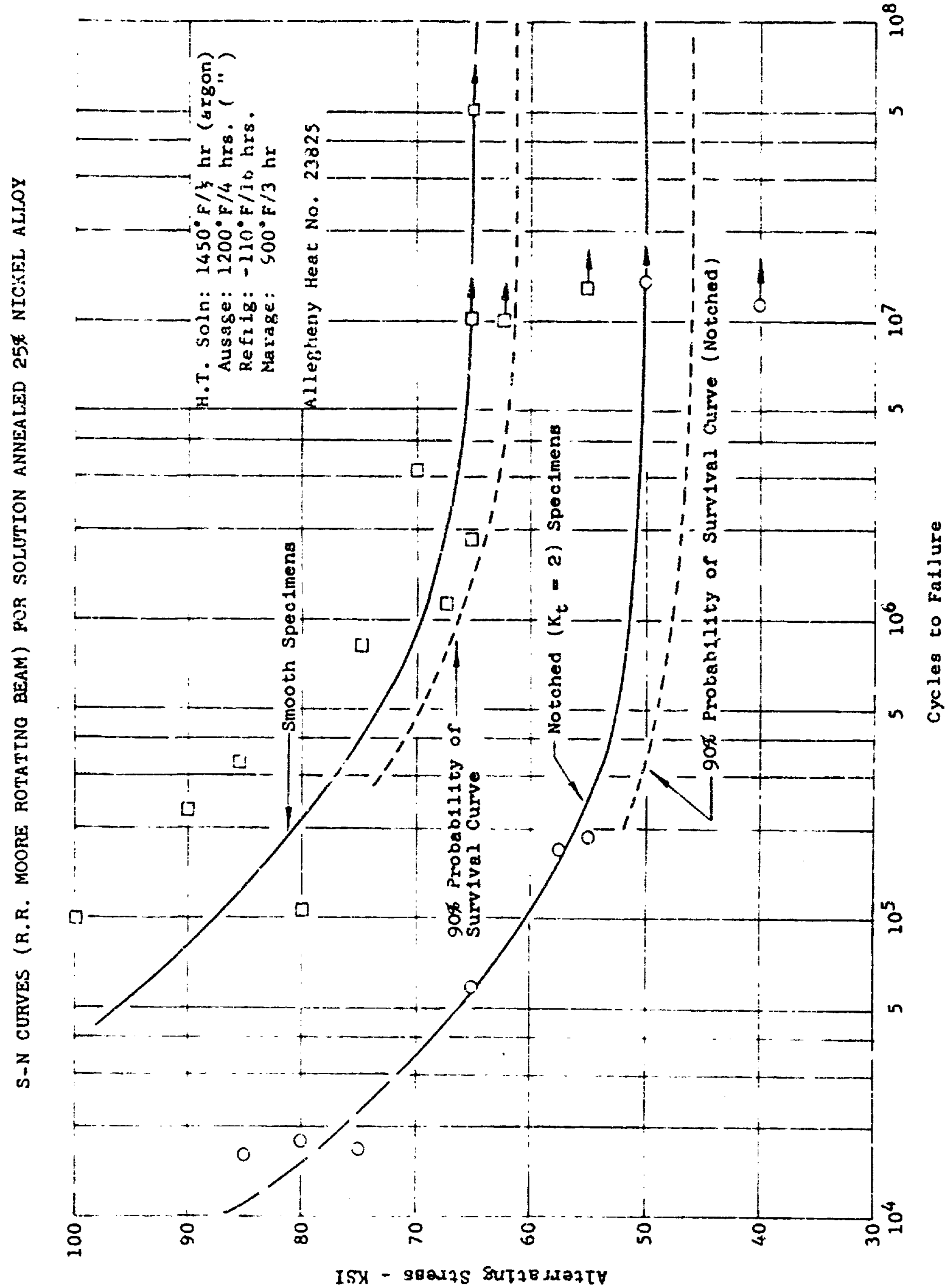

S-N CURVES (R.R. MOORE ROTATING BEAM) FOR SOLUTION ANNEALED 25% NICKEL ALLOY
H.T. Soln: 1450°F/½ hr (argon)
Ausage: 1200°F/4 hrs. (")
Refrig: -110°F/16 hrs.
Marage: 900°F/3 hr
Allegheny Heat No. 23825
Smooth Specimens
90% Probability of Survival Curve
Notched (K_t = 2) Specimens
90% Probability of Survival Curve (Notched)
Alternating Stress - KSI
Cycles to Failure
100
90
80
70
60
50
40
30
10^4
5
10^5
5
10^6
5
10^7
5
10^8

Figure 207

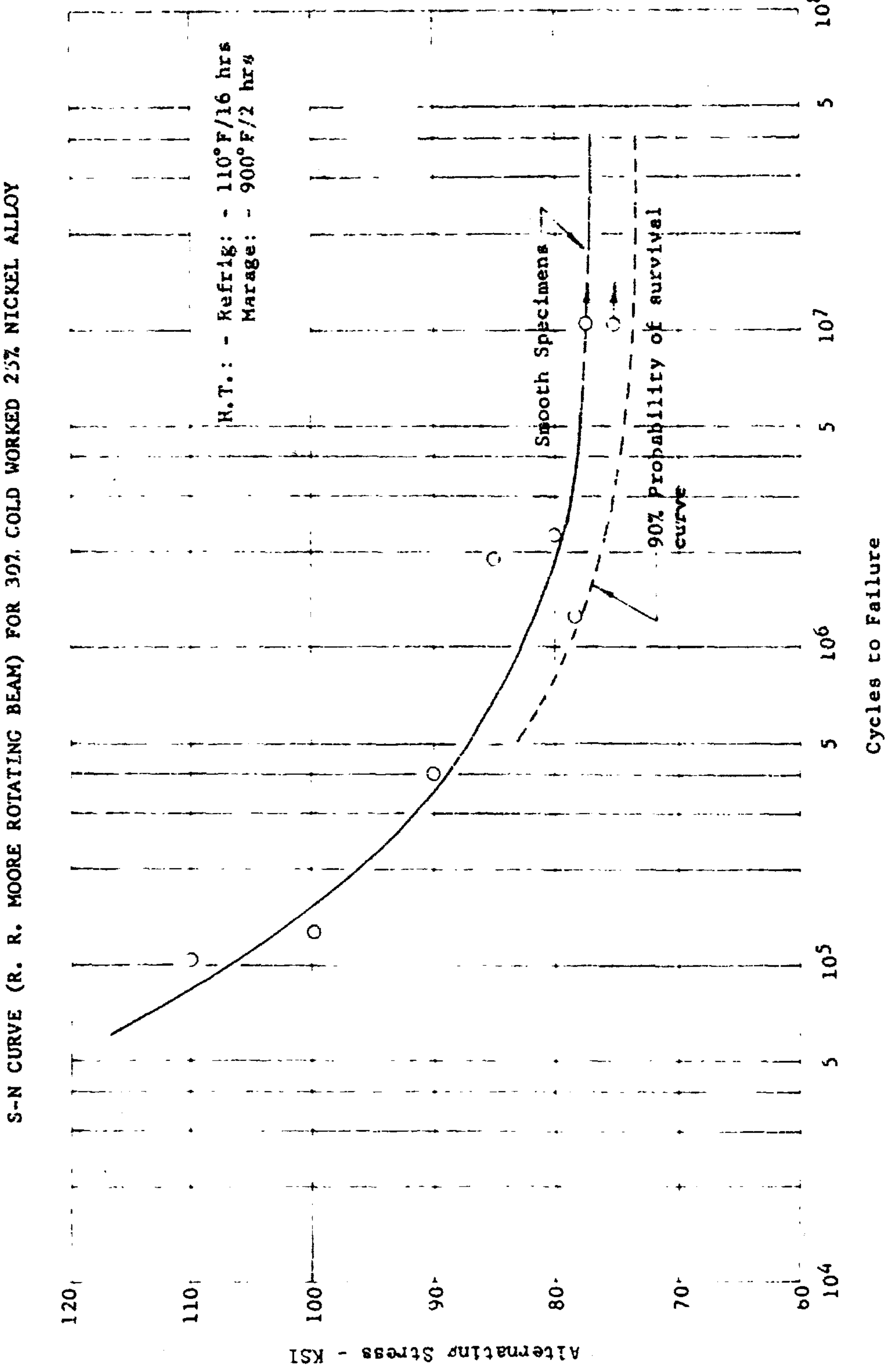
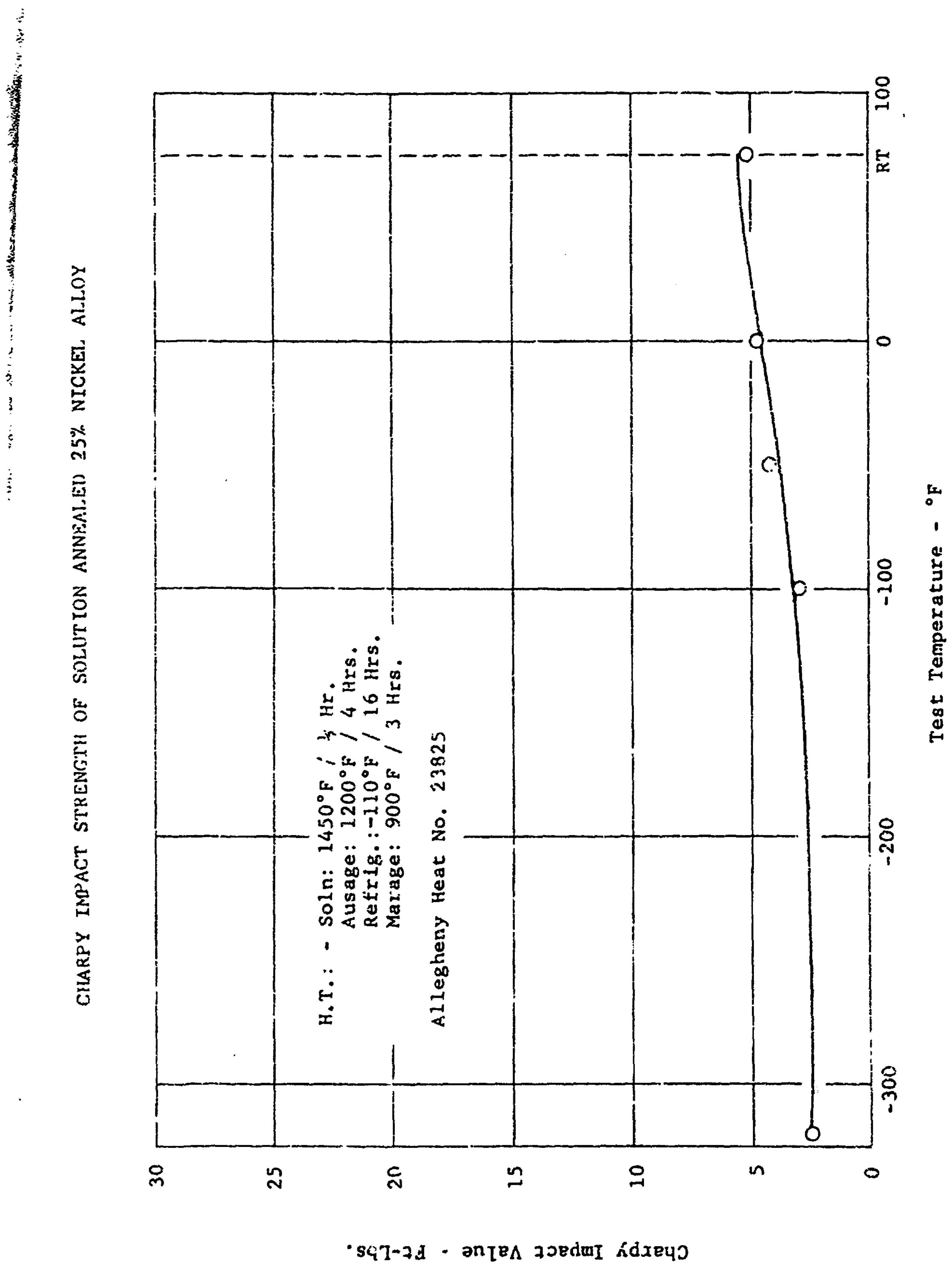

S-N CURVE (R. R. MOORE ROTATING BEAM) FOR 30% COLD WORKED 25% NICKEL ALLOY
H.T.: - Refrig: - 110°F/16 hrs
Marage: - 900°F/2 hrs
Smooth Specimens
90% Probability of survival curve
Cycles to Failure
Alternating Stress - KSI
120
110
100
90
80
70
60
10^4
5
10^5
5
10^6
5
10^7
5
10^8

Figure 208



CHARPY IMPACT STRENGTH OF SOLUTION ANNEALED 25% NICKEL ALLOY
H.T.: - Soln: 1450°F / ½ Hr.
Ausage: 1200°F / 4 Hrs.
Refrig.: -110°F / 16 Hrs.
Marage: 900°F / 3 Hrs.
Allegheny Heat No. 23825
Charpy Impact Value - Ft-Lbs.
30
25
20
15
10
5
0
Test Temperature - °F
100
RT
0
-100
-200
-300

Figure 209

CHARPY IMPACT STRENGTH OF COLD WORKED 25% NICKEL ALLOY

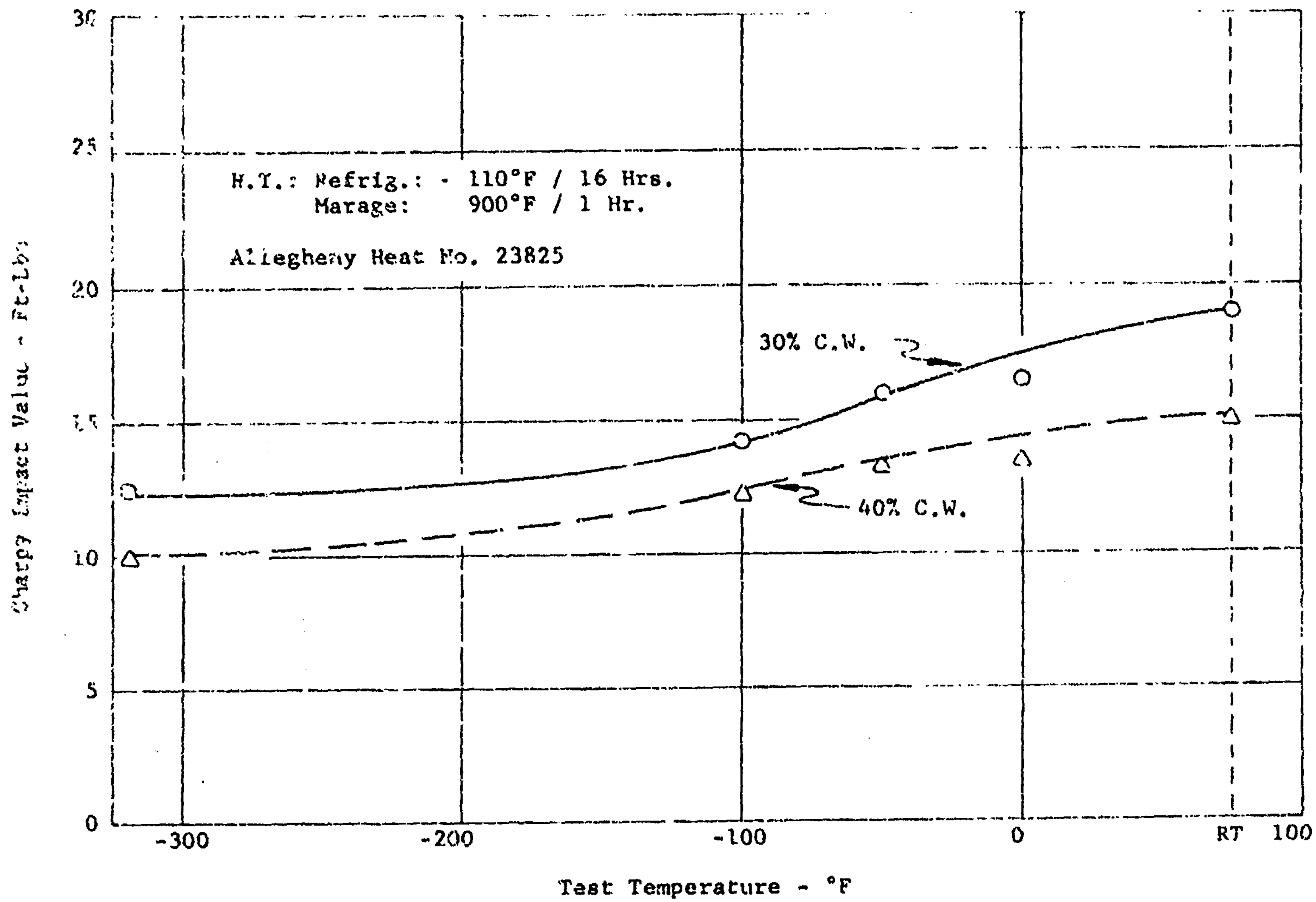


Figure 210

COMPARISON OF FRACTURE TOUGHNESS OF 25% NICKEL ALLOY
IN COLD WORK AND ANNEALED CONDITIONS

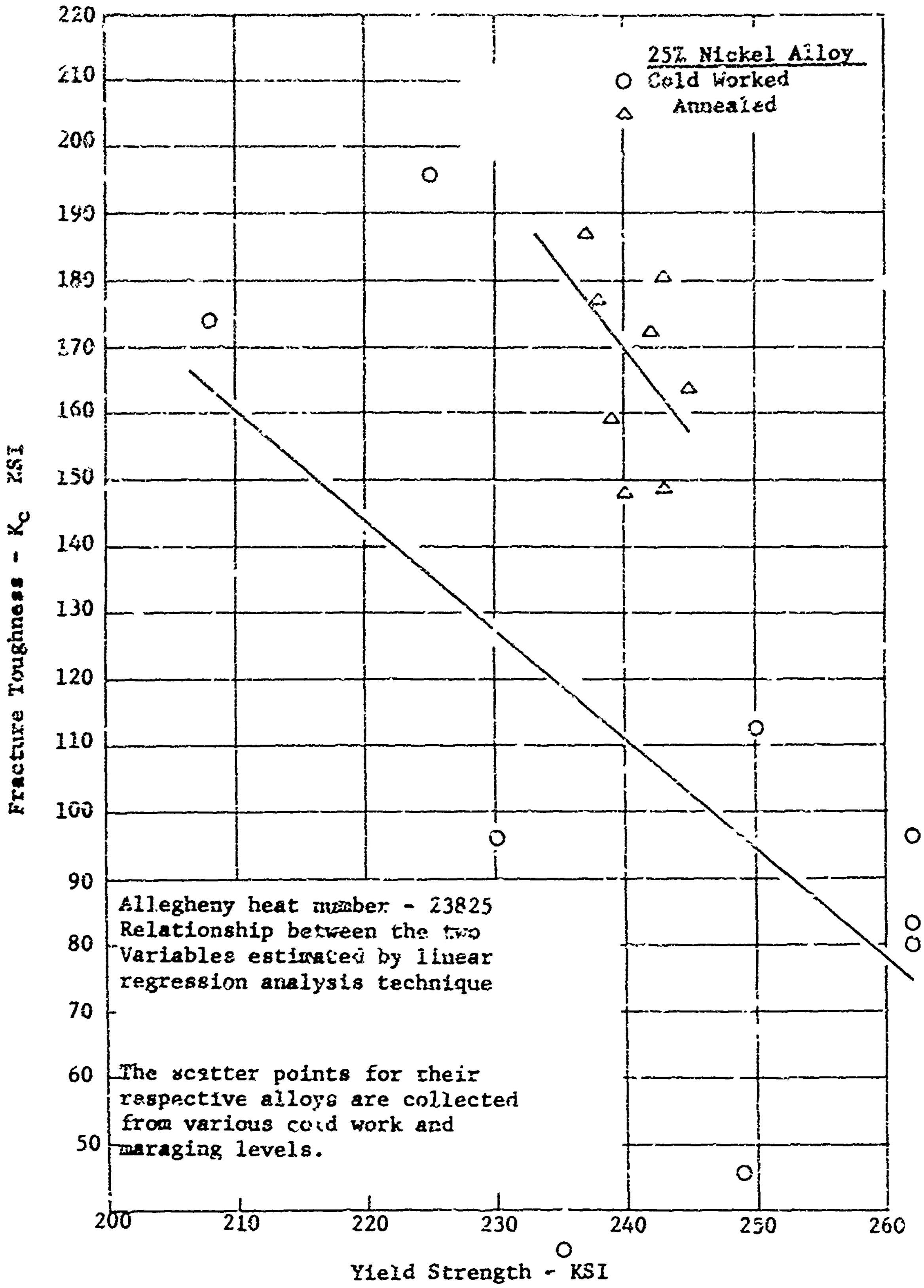


Figure 211

5358

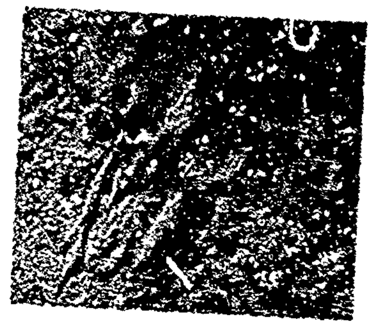
MICROSTRUCTURE OF 25% NICKEL ALLOY

Solutioned 1500°F/1 hr.

Mag. 500 X

Etchant: Marble's + Modified Fry's

Solutioned 1500°F/1 hr.



Mag. 18000 X

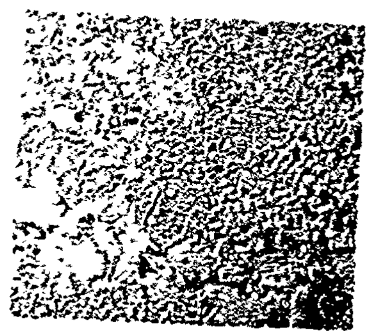
Two Stage Carbon Replica

Solutioned 1500°F/1 hr.,
Ausaged 1300°F/4 hrs.

Mag. 500 X

Etchant: Marble's + Modified Fry's

Sol[illegible] 1500°F/1 hr.,
Ausaged 1300°F/4 hrs.



Mag. 18000 X

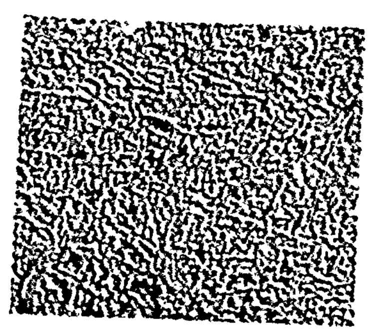
Two Stage Carbon Replica

Sol'n. 1500°F/1 hr., Aus. 1300°F/4 hrs.
R. -110°F/16 hrs., Mar. 900°F/3 hrs.

Mag. 500 X

Etchant: Marble's + Modified Fry's

Sol'n. 1500°F/1 hr., Aus. 1300°F/4 hrs.
R. -110°F/16 hrs., Mar. 900°F/3 hrs.



Mag. 18000 X

Two Stage Carbon Replica

Figure 212

25% NICKEL ALLOY WELD HARDNESS DATA
VERTICAL TRAVERSES ALONG WELD CENTERLINE

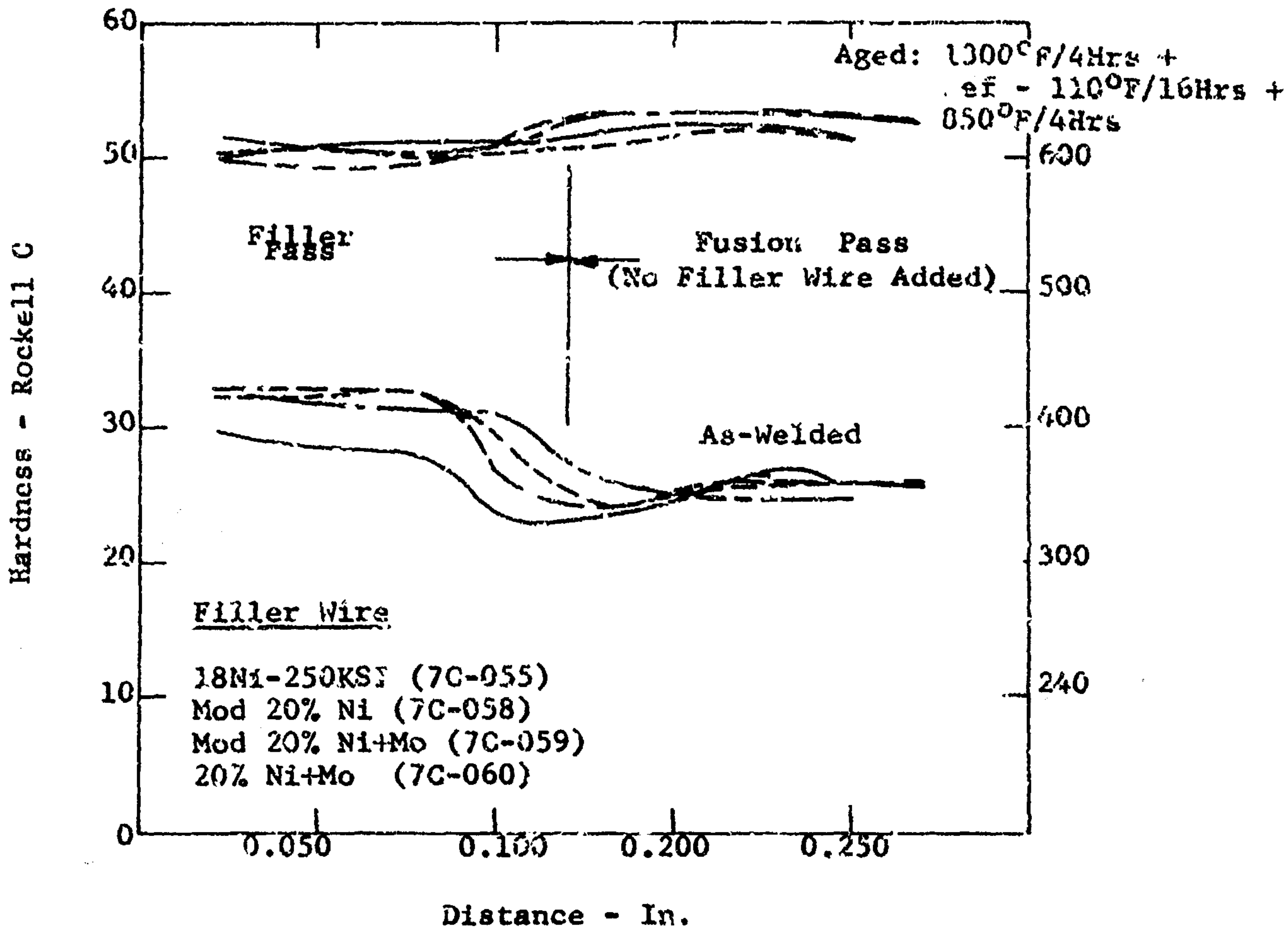


Figure 213

WELD ZONE HARDNESS SURVEY
25% NICKEL ALLOY - SOLUTION HEAT TREATED
(COMPOSITE OF 4 SURVEYS)

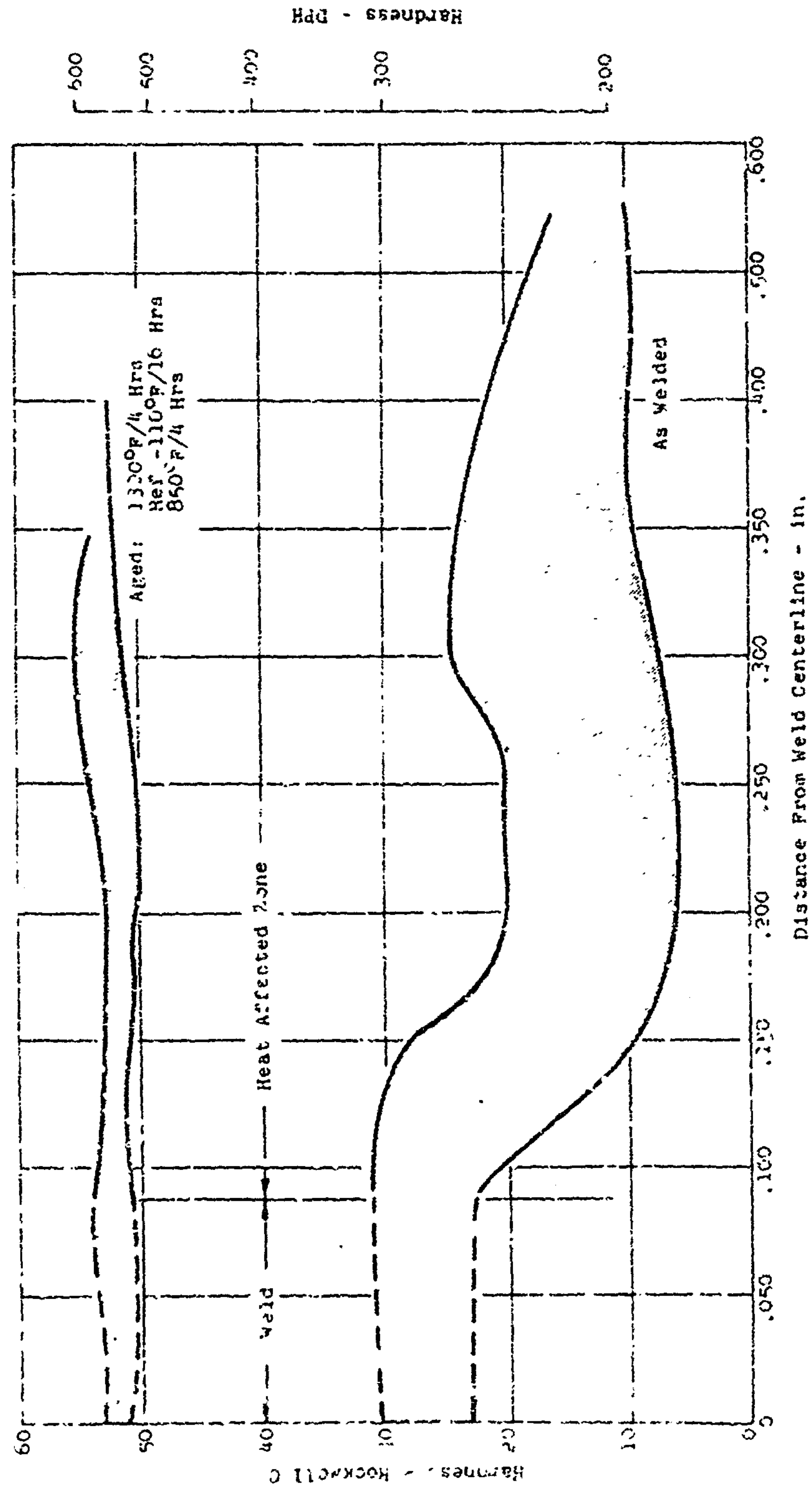
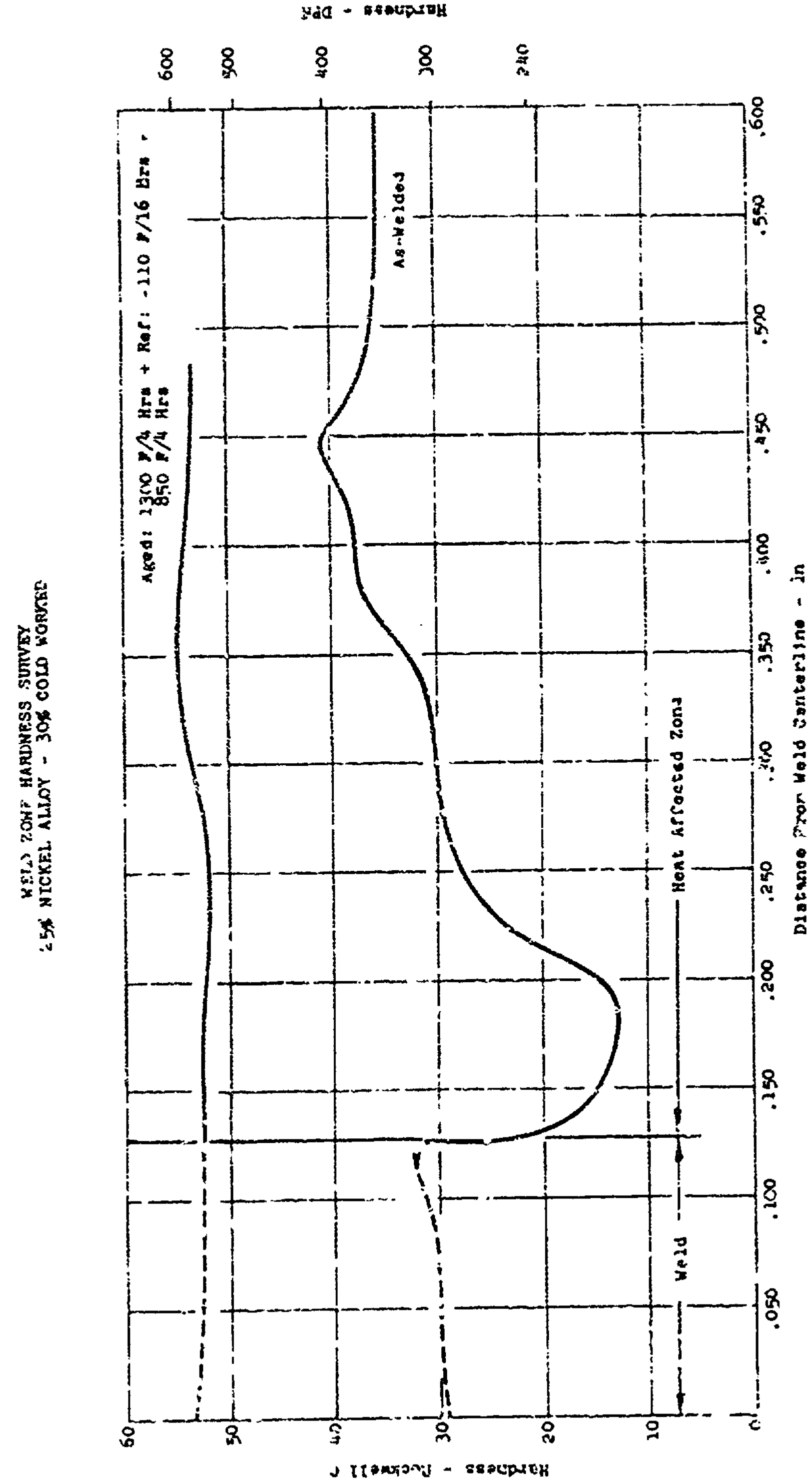


Figure 214



WELD ZONE HARDNESS SURVEY
25% NICKEL ALLOY - 30% COLD WORKED
Hardness - DPH
600
500
400
300
240
Aged: 1300 F/4 Hrs + Ref: -110 F/16 Hrs + 850 F/4 Hrs
As-Welded
Heat Affected Zone
Weld
Distance From Weld Centerline - in
.050
.100
.150
.200
.250
.300
.350
.400
.450
.500
.550
.600
Hardness - Rockwell C
60
50
40
30
20
10
0

Figure 215

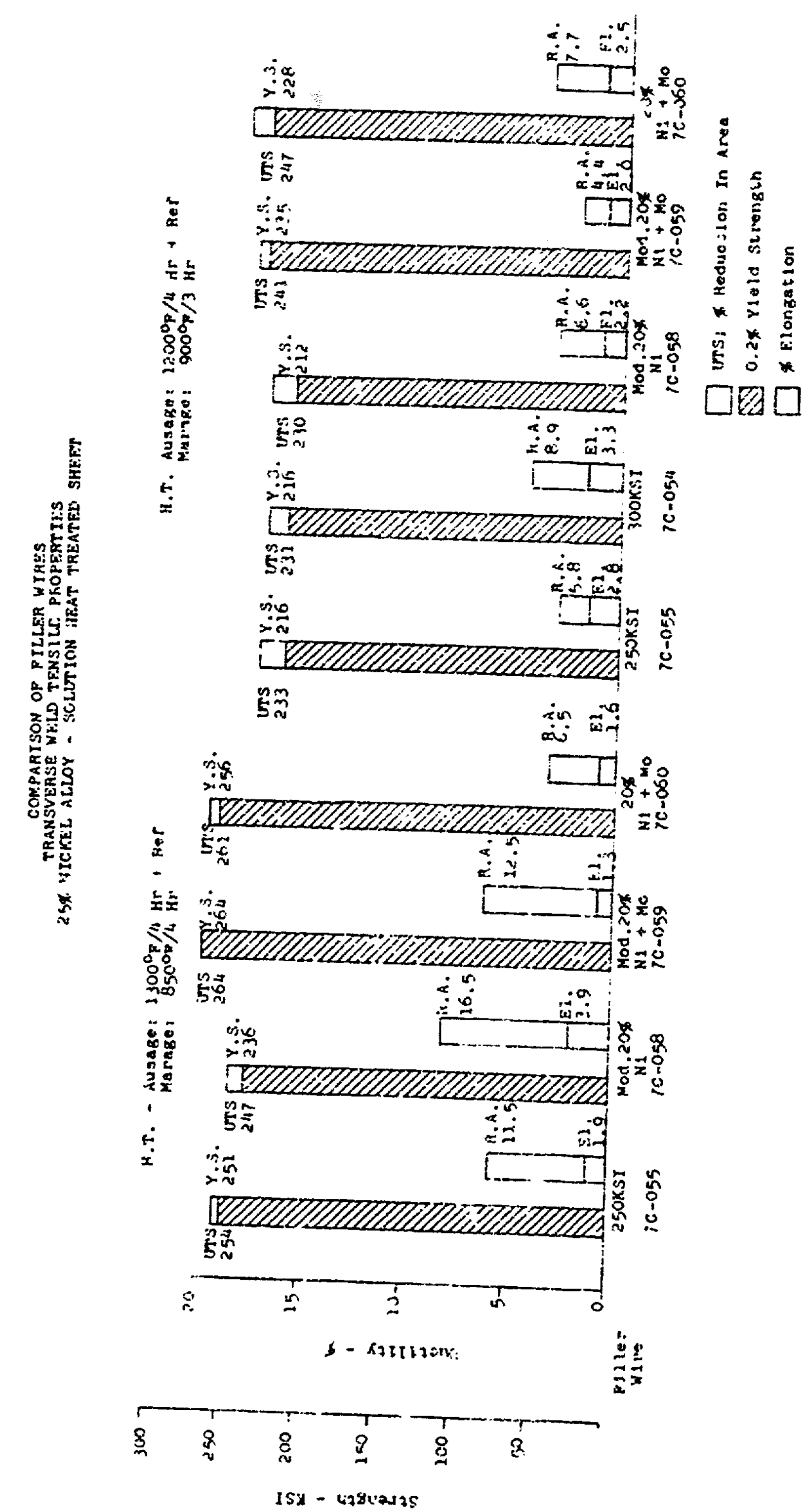

COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE PROPERTIES
25% NICKEL ALLOY - SOLUTION HEAT TREATED SHEET
H.T. - Ausage: 1300°F/4 Hr + Ref
Marage: 850°F/4 Hr
H.T. Ausage: 1200°F/4 Hr + Ref
Marage: 900°F/3 Hr
Strength - KSI
Ductility - %
Filler Wire
UTS 254
Y.S. 251
R.A. 11.5
El. 1.9
250KSI
7C-055
UTS 247
Y.S. 236
R.A. 16.5
El. 3.9
Mod.20% Ni
7C-058
UTS 264
Y.S. 264
R.A. 12.5
El. 1.3
Mod.20% Ni + Mo
7C-059
UTS 261
Y.S. 256
R.A. 6.5
El. 1.6
20% Ni + Mo
7C-060
UTS 233
Y.S. 216
R.A. 5.8
El. 2.8
250KSI
7C-055
UTS 231
Y.S. 216
R.A. 8.9
El. 3.3
300KSI
7C-054
UTS 230
Y.S. 212
R.A. 6.6
El. 2.2
Mod.20% Ni
7C-058
UTS 241
Y.S. 235
R.A. 4.4
El. 2.0
Mod.20% Ni + Mo
7C-059
UTS 247
Y.S. 228
R.A. 7.7
El. 2.5
20% Ni + Mo
7C-060
UTS; % Reduction In Area
0.2% Yield Strength
% Elongation

Figure 216

COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE PROPERTIES
25% NICKEL ALLOY - 30% COLD WORKED - .140" SHEET (1) (2)

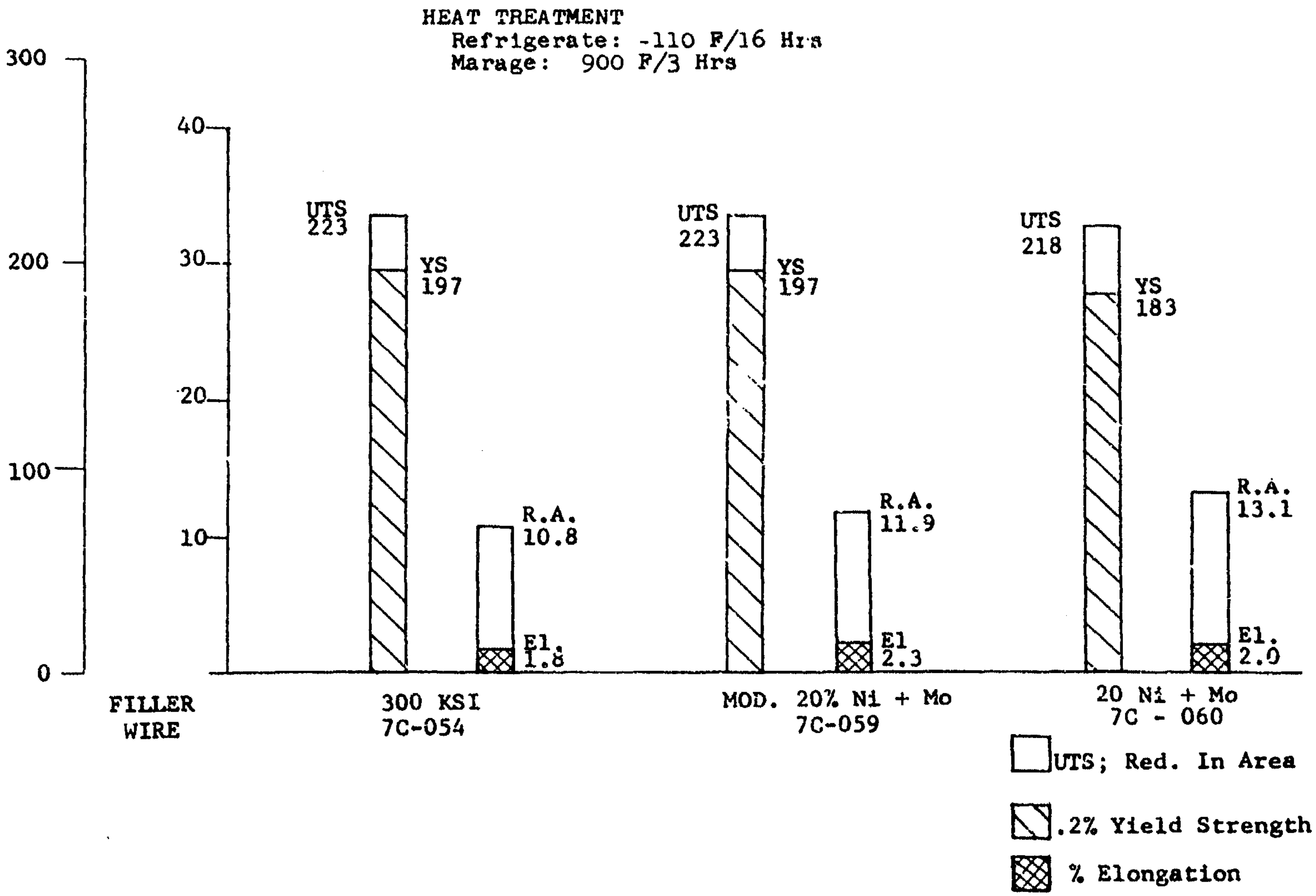
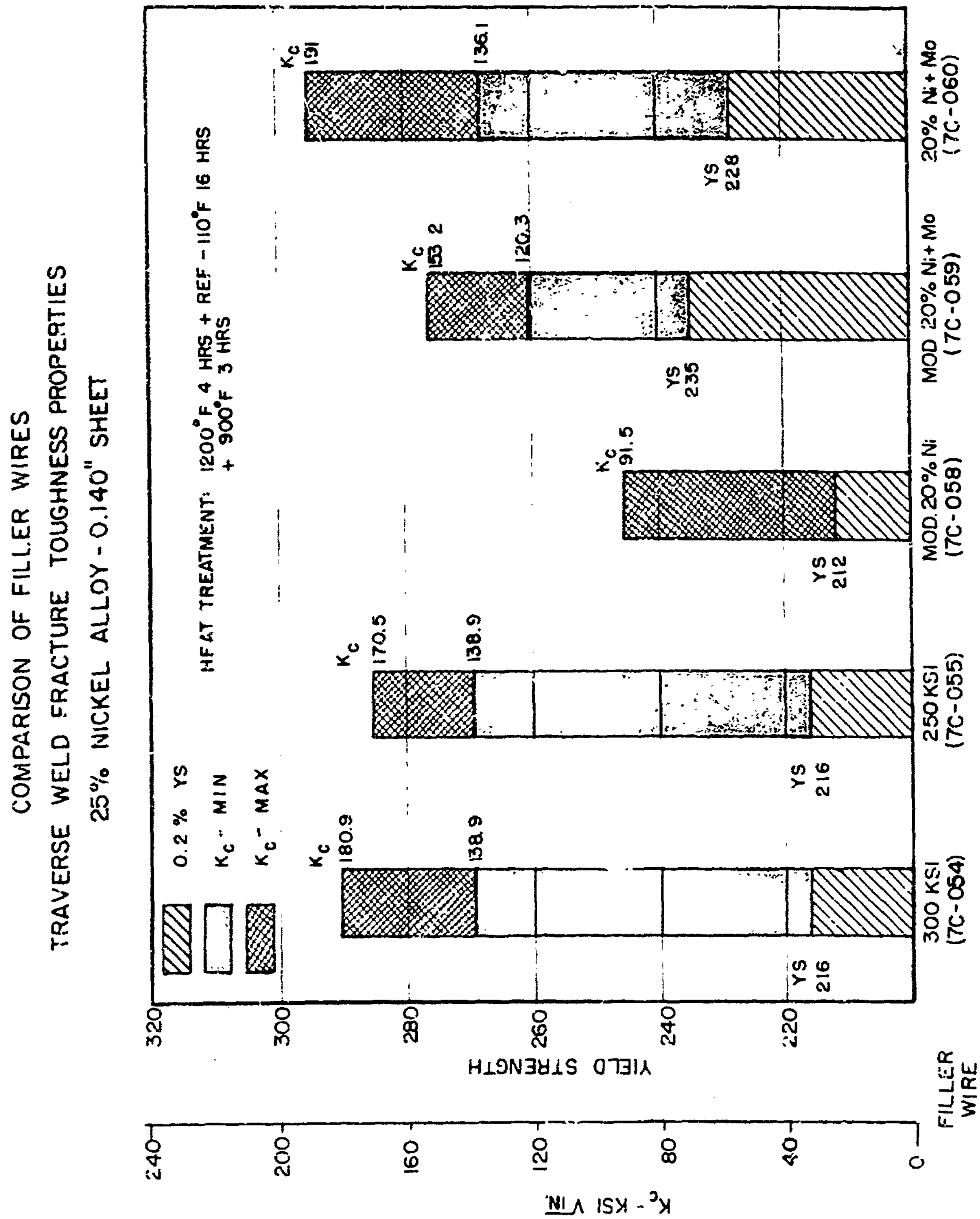


Figure 217



COMPARISON OF FILLER WIRES
TRAVERSE WELD FRACTURE TOUGHNESS PROPERTIES
25% NICKEL ALLOY - 0.140" SHEET
HEAT TREATMENT: 1200°F 4 HRS + REF - 110°F 16 HRS + 900°F 3 HRS
0.2 % YS
Kc - MIN
Kc - MAX
YIELD STRENGTH
320
300
280
260
240
220
Kc - KSI √IN.
240
200
160
120
80
40
0
FILLER WIRE
Kc 180.9
138.9
YS 216
300 KSI (7C-054)
Kc 170.5
138.9
YS 216
250 KSI (7C-055)
Kc 91.5
YS 212
MOD. 20% Ni (7C-058)
Kc 153.2
120.3
YS 235
MOD 20% Ni + Mo (7C-059)
Kc 191
136.1
YS 228
20% Ni + Mo (7C-060)

Figure 218

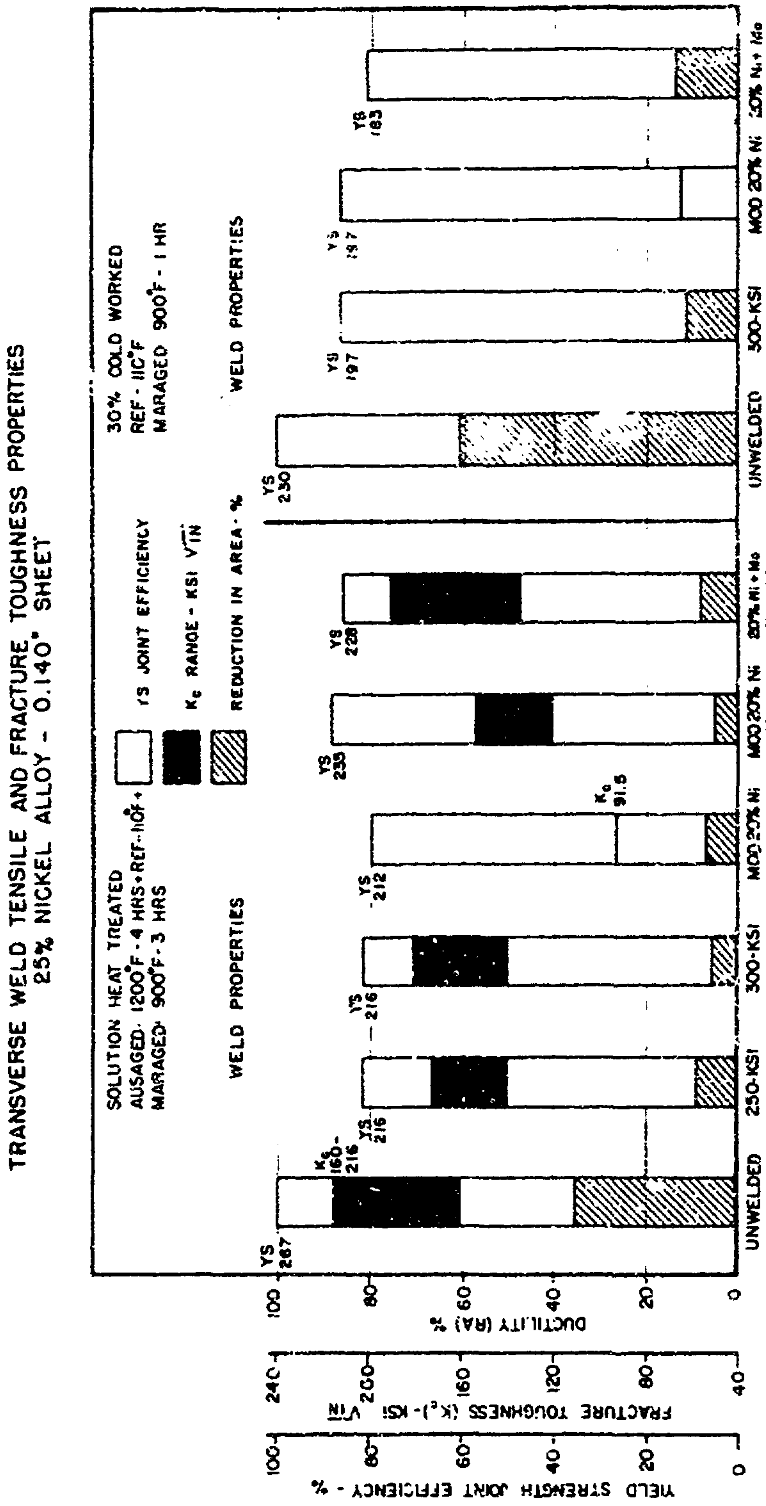

COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE AND FRACTURE TOUGHNESS PROPERTIES
25% NICKEL ALLOY - 0.140" SHEET
SOLUTION HEAT TREATED
AUSAGED: 1200°F - 4 HRS + REF - 110°F +
MARAGED: 900°F - 3 HRS
WELD PROPERTIES
YS JOINT EFFICIENCY
Kc RANGE - KSI √IN
REDUCTION IN AREA - %
30% COLD WORKED
REF - 110°F
MARAGED 900°F - 1 HR
WELD PROPERTIES
YS 267
Kc 160-216
YS 216
YS 216
YS 212
Kc 91.5
YS 235
YS 228
YS 230
YS 197
YS 197
YS 183
UNWELDED SHEET (LONGITUDINAL) PROPS
250-KSI 7C-055
300-KSI 7C-054
MOD 20% Ni 7C-058
MOD 20% Ni + Mo 7C-059
20% Ni + Mo 7C-60
UNWELDED SHEET (LONGITUDINAL) PROPS
300-KSI 7C-054
MOD 20% Ni + Mo 7C-059
20% Ni + Mo 7C-060
DUCTILITY (RA) %
FRACTURE TOUGHNESS (Kc) - KSI √IN
YIELD STRENGTH JOINT EFFICIENCY - %

Figure 219

Table 112

EFFECT OF SOLUTION TIME AND TEMPERATURE ON THE HARDNESS OF 25% Ni ALLOY*

Solution Temp. °F	Solution Time Hrs.	As Quenched Hardness Ra	Maraged** Hardness Rc
1300	¼	68.4	51.8
	½	68.4	51.6
	1	69.8	51.8
	2	69.9	51.7
	4	69.9	51.8
1400	¼	64.5	51.4
	½	64.8	51.3
	1	63.9	51.5
	2	63.6	51.0
	4	63.0	51.0
1500	¼	61.6	50.9
	½	61.0	51.2
	1	59.4	50.8
	2	49.6	50.9
	4	46.4	50.2
1600	¼	56.0	50.2
	½	48.5	51.1
	1	46.3	51.0
	2	46.1	51.0
	4	45.7	50.0
1700	¼	45.5	49.9
	½	44.0	51.2
	1	43.2	50.8
	2	42.4	50.8
	4	42.0	50.6
1800	¼	43.3	49.8
	½	43.9	49.9
	1	45.8	50.0
	2	57.7	49.9
	4	60.0	49.8
1900	¼	42.0	49.0
	½	46.1	48.9
	1	59.4	49.1
	2	60.3	50.0
	4	61.1	49.8

Table 112 (Cont.)

EFFECT OF SOLUTION TIME AND TEMPERATURE ON THE HARDNESS OF 25% Ni ALLOY*

Solution Temp. °F	Solution Time Hrs.	As Quenched Hardness Ra	Maraged** Hardness Rc
2000	¼	61.3	50.1
	½	61.0	49.7
	1	61.6	50.0
	2	62.0	50.1
	4	61.8	49.6

* Allegheny Heat No. 23825

** Based on an average of 6 readings

Table 113

EFFECT OF AUSAGING TIME AND TEMPERATURE ON THE HARDNESS OF 25% Ni ALLOY*

Ausaging Temp °F	Ausaging Time Hrs.	As Quenched Hardness Rc	Maraged Hardness Rc
1100	1	40.1	51.0
	2	41.1	51.2
	3	41.0	51.5
	4	39.8	51.5
	8	43.3	52.1
	12	43.8	51.8
	16	43.8	51.6
1200	1	41.7	52.3
	2	42.3	52.2
	3	42.9	52.1
	4	42.3	52.1
	8	42.7	52.1
	12	42.6	51.8
1300	1	40.2	52.7
	2	40.1	52.4
	3	39.9	52.3
	4	40.2	52.5
	8	38.9	52.6
1400	1	29.4	52.9
	2	28.5	52.8
	3	27.4	52.8
	4	28.2	51.6

* Allegheny Heat No. 23825

Table 114

EFFECT OF REFRIGERATION TIME AND TEMPERATURE
ON THE HARDNESS OF 25% Ni ALLOY*

Refrig. Temp. °F	Refrig. Time Hrs.	Hardness After Estab. Of Equil. (24 Hrs.)	Maraged Hardness
-115	1	34.4	51.0
	2	32.4	50.9
	3	35.1	51.1
	4	36.4	51.1
-50	1	36.5	50.8
	2	37.5	50.7
	3	39.0	51.0
	4	39.2	51.0
	8	38.8	51.1
	12	37.4	49.9
	16	37.2	50.0
0	1	38.1	50.1
	2	34.6	49.8
	3	37.8	49.8
	4	35.6	50.2
	8	39.8	51.0
	12	38.5	50.4
	16	37.1	50.1

* Allegheny Heat No. 23825

Table 115

EFFECT OF MARAGING PARAMETERS ON THE HARDNESS OF SOLUTION ANNEALED** 25% NI ALLOY*

Maraging Temp. °F	Maraging Time Hrs.	Hardness Rc
700	¼	46.3
	½	45.3
	1	45.9
	2	48.1
	5	49.4
800	¼	47.9
	½	50.2
	1	50.2
	2	51.4
	5	51.5
900	¼	50.7
	½	51.6
	1	51.8
	2	51.1
	5	49.7
1000	¼	47.5
	½	48.2
	1	48.9
	2	46.1
	5	48.0

* Allegheny Heat No. 23825

** All specimens solution annealed: 1500°F/1 hr.

Table 116

EFFECT OF SOLUTIONING, AUSAGING, AND MARAGING PARAMETERS ON LONGITUDINAL TENSILE PROPERTIES OF 25% NICKEL ALLOY *

Solution Temp. °F	Solution Time Hrs.	Ausage Temp ** °F	Ausage Time Hrs.	Marage Temp °F	Marage Time Hrs.	Ult. Tensile Strength KSI	.2% Yield Strength KSI	% Elong.	% R.A.
1400	½	1200	4	800	1	297	270	8	30
		"	4			293	276	6	32
		1300	4			259	246	7	35
		"	4			260	244	6	36
		1200	4	900	3	232	219	9	38
		"	4			244	196	7	34
				950	4	275	252	5	27
						277	244	8	34
		1300	4			262	251	6	31
		"	4			260	246	6	35
1400	1	1300	4	900	3	269	251	4	28
						264	255	3.7	29
						262	256	4	33
						270	268	3.9	33
1450	½	1200	4	900	3	244	225	8	37
		"	4			244	225	8	33
		1300	4			270	250	5	25
1500	½	1200	4			246	249	5	17
		"	4			248	220	6	33
		1300	4			271	260	4	27
		"	4			267	264	5	26
1500	½	1200	4			248	232	5	32
		"	4			252	228	6	33
1500	1	1200	4			285	268	4	25
		"	4			275	254	4	15
		1300	4			267	222	4	25
		"	4			273	262	4.2	23
1500	1	1300	4	900	3	267	260	3.9	27
			4			276	268	3.7	45
			4			278	273	5.3	39
			4			276	265	5.8	42

EFFECT OF SOLUTIONING, AUSAGING, AND MARAGING PARAMETERS ON LONGITUDINAL TENSILE PROPERTIES OF 25% NICKEL ALLOY * (Cont'd.)

Solution Temp. °F	Solution Time Hrs.	Ausage Temp** °F	Ausage Time Hrs.	Marage Temp °F	Marage Time Hrs.	Ult. Tensile Strength KSI	.2% Yield Strength KSI	% Elong.	% R.A.
1550	½	1200	4	900	3	269	238	3.9	20
		"	4			267	259	4.9	27
		1300	4			272	266	4.7	33
		"	4			266	257	5.0	33
1600	½	1200	4	800	1	272	246	3	9
		"	4	"	1	287	260	3	6
		1300	4	"	1	225	191	9	41
		"	4	"	1	243	221	11	41
		1200	4	900	3	264	258	13	20
		"	4	"	3	272	211	13	21
		1200	4	950	4	277	271	9	19
		"	4	"	4	293	282	4	10
		1300	4	"	4	249	241	8	48
		"	4	"	4	244	230	8	40
1600	1	1300	4	900	3	278	261	6.7	22
		"	4	"	3	281	265	6.4	34
		"	4	"	3	266	255	6.0	40
		"	4	"	3	273	259	6.3	37
1700	1	1300	4	900	3	244	231	6.1	51
		"	4	"	3	250	236	5.8	48
		"	4	"	3	253	237	5.7	41
		"	4	"	3	250	234	5.7	46

* Allegheny Heat No. 23825

** All specimens refrigerated (-110°F/16 hrs) after the ausaging treatment.

Table 117

EFFECT OF SOLUTIONING, AUSAGING, AND MARAGING PARAMETERS ON TRANSVERSE TENSILE PROPERTIES OF 25% NICKEL ALLOY*

Solution Temp. °F	Solution Time Hrs.	Ausage Temp ** °F	Ausage Time Hrs.	Marage Temp °F	Marage Time Hrs.	Ult. Tensile Strength KSI	.2% Yield Strength KSI	% Elong.	% R.A.
1400	½	1200	4	900	3	261	236	5	25
		"	4	900	3	243	217	5	21
1400	1	1300	4	900	3	282	276	4	24
		"	4	"	3	286	283	3.6	27
		"	4	"	3	284	278	3.6	22
		"	4	"	3	287	279	4.2	23
1450	½	1200	4	"	3	252	237	4.0	23
		"	4	"	3	253	229	5.0	24
		1300	4	"	3	280	267	4.4	20
		"	4	"	3	281	270	3.0	24
1500	½	1200	4	"	3	260	237	5.4	23
		"	4	"	3	254	237	3.0	23
		1300	4	"	3	286	273	4.2	23
		"	4	"	3	290	276	4.0	23
	½	1200	4	"	3	258	237	4.2	23
		"	4	"	3	266	244	5.0	21
1500	1	1200	4	"	3	293	275	3.0	10
		"	4	"	3	291	278	4.0	15
		1300	4	"	3	296	286	3.6	15
		"	4	"	3	287	278	3.0	
		"	4	"	3	279	265	4.4	29
		"	4	"	3	293	285	4.7	27
1550	½	1200	4	"	3	279	250	5.0	13
		"	4	"	3	286	263	5.4	17
		1300	4	"	3	286	272	3.5	19
		"	4	"	3	270	263	3.0	18
1600	½	1200	4	"	3	264	216	3.0	9
		"	4	"	3	275	228	5.0	8
		1300	4	"	3	283	272	5.2	20
		"	4	"	3	288	275	5.1	18
		"	4	"	3	283	265	5.6	33
		"	4	"	3	284	267	6.1	25

Table 117 (Cont.)

EFFECT OF SOLUTIONING, AUSAGING, AND MARAGING PARAMETERS ON TRANSVERSE TENSILE PROPERTIES OF 25% NICKEL ALLOY

Solution Temp. °F	Solution Time Hrs.	Ausage Temp ** °F	Ausage Time Hrs.	Marage Temp °F	Marage Time Hrs.	Ult. Tensile Strength KSI	.2% Yield Strength KSI	% Elong.	% R.A.
1700	1	1300	4	900	3	259	245	4.7	29
		"	4			260	233	5.1	37
		"	4			264	235	5.2	36
		"	4			263	240	5.7	43

* Allegheny Heat No. 23825

** All specimens refrigerated (-110°F/16 hrs) after the ausaging treatment.

Table 118

EFFECT OF SOLUTIONING AND AUSAGING PARAMETERS ON LONGITUDINAL FRACTURE TOUGHNESS OF 25% NICKEL ALLOY*

Ausaging Temp. °F	Ausaging Time Hrs.	Solution Temp. °F	Solution Time Hrs.	0.2% Yield Str. KSI	Net Fracture Stress(1) KSI	Notch Strength(2) KSI	β (3)	Critical Crack Index(4)	Kc (5) KSI$\sqrt{in}$	Gc (6) + In-lb/in^2
1200	4	1400	½	208	284.9	124.2	6.55	0.24	181.7	1,501
		-	"	208	315	122.2	6.95	0.260	186.8	1,586
		1450	½	225	534	127.5	7.99	0.290	215.8	2,117
		-	"	225	243.1	117.9	4.47	0.160	159.3	1,153
		1500	½	225	144.4	103.1	1.91	0.070	104.6	497.5
		-	"	225	149.1	105	2.04	0.070	107.4	524.7
		1500	½	230	134.7	104	1.61	0.059	99.3	448.1
		-	"	230	175.2	99.7	2.10	0.077	113.0	580
		1500	1	261	46.2	37.1	0.14	0.005	33.0	49.5
		-	"	261	49.4	39.4	0.16	0.006	35.3	56.7
		1550	½	249	76.6	57.9	0.40	0.015	54.2	1,335
		-	"	249	91.5	51.7	0.46	0.017	57.6	151
		1600	½	235	60.1	42.8	0.29	0.010	42.1	80.5
		-	"	235	72.4	41.1	0.34	0.012	46.0	96.5
1300	4	1450	½	250	130.5	99.1	1.28	0.046	95.2	412.3
		-	"	250	310.9	102.9	3.09	0.115	150.0	1,022
		1500	½	262	222.3	78.3	1.26	0.046	99.8	453
		-	"	262	187.4	66.8	0.93	0.034	86.1	327.2
		1500	½							
		-	"							
		1500	1	262	191.5	71.4	1.11	0.042	94.6	406.4
		-	"	262	151.4	70.4	0.91	0.033	84.9	327.5
		1550	½	262	204.2	85.5	1.46	0.054	108.2	532
		-	"	262	209.4	81.2	1.35	0.054	104.3	494.4

* Allegheny Heat No. 23825

\+ Centrally notched fatigue cracked specimen

** All specimens refrigerated @ - 110°F/16 hrs. and maraged 900°F/3 hrs.

Table 119

EFFECT OF SOLUTIONING AND AUSAGING PARAMETERS ON TRANSVERSE FRACTURE TOUGHNESS OF 25% NICKEL ALLOY*

Ausaging Temp. °F	Ausaging Time Hrs.	Solution Temp. °F	Solution Time Hrs.	0.2% Yield Str. KSI	Net Fracture Stress (1) KSI	Notch Strength (2) KSI	β (3)	Critical Crack Index (4)	Kc (5) KSI$\sqrt{In}$	Gc (6)+ In-lb/in^2
1200	4	1400	½	227	199.5	122.3	3.002	0.120	139.5	884.8
				227	143.2	99.3	1.63	0.060	101.5	468.2
		1500	1	275	54.3	41.2	0.15	0.006	38.3	66.8
				275	53.6	37.1	0.14	0.006	36.4	60.2
		1550	½	257	80.7	55.4	0.39	0.015	56.3	144.0
				257	76.7	52.0	0.33	0.013	52.0	122.7
		1600	½	222	65.8	49.3	0.38	0.015	47.3	101.8
				222	77.7	57.8	0.50	0.019	55.2	138.6
1300	4	1450	½	269	100.1	82.2	0.61	0.024	73.5	245.5
				269	88.5	63.1	0.43	0.017	61.9	174.1
		1500	1	286	49.9	36.1	0.11	0.004	33.1	49.8
				286	62.7	45.1	0.19	0.007	43.4	85.7

* Allegheny Heat No. 23825

\+ Centrally notched fatigue cracked specimen

** All specimens refrigerated @ - 110°F/16 hrs. and maraged 900°F/3 hrs.

Table 120

EFFECT OF SMALL AMOUNTS OF RETAINED AUSTENITE ON THE LONGITUDINAL TENSILE PROPERTIES OF 25% NICKEL ALLOY*

% Reduction	Approximate** Amts. of Retained Austenite	Marage Temp. °F	Marage Time Hrs.	Ultimate Tensile Strength KSI	0.2% Y.S. KSI	% Elong.	% R.A.
30	17.3	850	1.75	181	142	9	65
	"	900	"	179	170	10	67
	"	"	"	182	139	10	66
	"	950	"	151	129	12	67
	"	"	"	176	152	12	54
40	9.2	850	"	216	152	8	46
	"	"	"	211	165	9	48
	"	900	"	194	156	9	60
	"	"	"	213	174	7	61
	"	950	"	210	158	8	58
	"	"	"	197	156	10	61
50	3.7	850	"	212	159	8	56
	"	"	"	205	151	9	57
	"	900	"	204	165	8	56
	"	"	"	202	159	9	71
	"	950	"	210	162	8	53
	"	"	"	206	159	8	55

* Allegheny Heat No. 23825

** No refrigeration. Hence, indicated % retained austenite represent the amounts determined in the as cold worked condition.

Table 121

EFFECT OF SMALL AMOUNTS OF RETAINED AUSTENITE ON TRANSVERSE TENSILE PROPERTIES OF 25% NICKEL ALLOY*

% Reduction	Approximate Amts. of Retained Austenite** %	Marage Temp. °F	Marage Time Hrs.	Ultimate Tensile Strength KSI	0.2% Y.S.	% Elong.	% R.A.
30	17.3	850	1.75	156	142	12	51
		"	"	166	144	11	61
		900	"	163	137	8	54
		"	"	170	143	16	49
		950	"	151	129	10	52
40	9.2	850	"	194	164	7	44
		"	"	204	163	7	42
		900	"	209	178	6	42
		"	"	203	167	7	44
		950	"	193	165	7	47
		"	"	192	175	11	48
50	3.7	850	"	204	173	6	48
		"	"	201	163	7	45
		900	"	214	185	6	42
		"	"	203	155	5	45
		950	"	208	174	7	41
		"	"	195	150	9	47

* Allegheny Heat No. 23825

** No refrigeration. Hence, indicated % retained austenite represents the amounts determined in the as cold worked, condition

Table 122

ISOCHRONAL TRANSFORMATIONS OF RETAINED AUSTENITE
IN THE COLD WORKED 25% NICKEL ALLOY*

% Reduction	Refrig. Time Hrs.	Refrig. Temp. °F	% Retained Austenite
20	As C.W. (No Refrig.)		18.13
	½	0	4.0
	"	- 50	1.6
	"	-110	$\ll 1$
	1	0	1.9
	"	- 50	< 1
	"	-110	$\ll 1$
30	As C.W. (No Refrig.)		17.29
	½	0	3.1
	"	- 50	< 1
	"	-110	No Trace
	1	0	1.4
	"	- 50	$\ll 1$
	"	-110	No Trace
40	As C.W. (No Refrig.)		9.17
	½	0	< 1
	"	- 50	< 1
	"	-110	No Trace
	1	0	< 1
	"	- 50	$\ll 1$
	"	-110	No Trace
50	As C.W. (No Refrig.)		3.69
	½	0	1.2
	"	- 50	< 1
	"	-110	$\ll 1$
	1	0	1.
	"	- 50	< 1
	"	-110	$\ll 1$

* Allegheny Heat No. 23825

Table 123

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON LONGITUDINAL TENSILE PROPERTIES OF 25% NICKEL ALLOY *

% Reduction	Marage** Temp °F	Marage Time Hrs.	U.T.S. KSI	0.2% Yield Strength KSI	% Elong.	% R.A.
20	800	1	230	216	5.0	50
	"	1	233	218	7.0	52
	850	1	236	227	7.0	55
	"	1	245	239	5.0	55
	900	1	255	198	5.0	62
	"	1	266	236	5.0	68
	"	3	256	209	6.0	49
	"	3	250	207	7.0	50
	"	10	252	216	6.0	52
	"	10	249	211	7.0	53
	950	1	249	230	6.0	61
	"	1	255	235	6.0	61
	"	4	236	215	7.0	60
	"	4	234	213	7.0	61
30	800	1	242	235	3.0	48
	"	1	243	231	6.0	55
	850	1	250	238	7.0	55
	"	1	251	237	6.0	60
	900	1	273	233	5.0	63
	"	1	259	226	5.0	61
	"	3	264	230	6.0	53
	"	10	258	217	6.0	52
	"	10	261	242	6.0	55
	950	1	263	231	6.0	65
	"	1	259	240	6.0	61
	"	4	253	236	7.0	62
	"	4	287	258	6.0	58
40	800	1	252	231	5.0	41
	"	1	252	234	6.0	49
	850	1	262	244	5.0	51
	"	1	277	250	6.0	49

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON LONGITUDINAL TENSILE PROPERTIES OF 25% NICKEL ALLOY * (Cont'd.)

% Reduction	Marage Temp. °F	Marage Time Hrs.	U.T.S. KSI	2.0% Yield Strength KSI	% Elong.	% R.A.
40	900	1	275	249	7.0	53
	"	1	274	259	6.0	52
	"	3	256	209	6.0	49
	"	3	279	249	5.4	56
	"	10	266	213	5.0	49
	"	10	268	246	5.7	52
	950	1	285	246	5.0	49
	"	1	258	247	7.0	58
	"	4	260	247	7.0	51
	"	4	263	242	7.0	56
50	800	1	247	236	6.0	52
	"	1	248	236	5.0	59
	850	1	258	242	5.0	57
	"	1	259	245	5.0	55
	900	1	267	234	5.0	59
	"	1	266	252	6.0	59
	"	3	265	242	5.0	55
	"	10	265	243	5.6	52
	"	10	240	233	5.0	53
	950	1	262	244	5.0	60
	"	1	265	239	5.1	64
	"	4	250	224	6.0	59
	"	4	252	234	6.0	57

* Allegheny Heat No. 23825

** Refrigerated - 110°F/16 hrs. Negligible amounts of retained austenite found after refrigeration.

Table 124

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON TRANSVERSE TENSILE PROPERTIES OF 25% NICKEL ALLOY*

% Reduction	Marage Temp °F	Marage Time Hrs.	U.T.S. KSI	0.2% Yield Strength KSI	% Elong.	% R.A.
20	900	3	266	258	5	42
"	"	"	255	227	5	33
"	"	10	262	233	6	40
"	"	"	253	245	6	37
30	900	3	281	244	5	38
"	"	"	279	238	5	39
"	"	10	270	230	5	34
"	"	"	271	253	6	40
40	900	3	279	267	4	36
"	"	"	289	257	5	38
"	"	10	280	243	5	39
"	"	"	276	232	5	39
50	900	3	282	262	5	38
"	"	"	290	270	5	40
"	"	10	276	249	5	40
"	"	"	279	248	5	37

* Allegheny Heat No. 23825

** All specimens refrigerated @ - 110°F/16 hrs.

Table 125

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON LONGITUDINAL FRACTURE TOUGHNESS OF 25% NICKEL ALLOY*

Per-cent Reduction	Maraging Temp. °F	Maraging Time Hrs.	0.2% Yield Str. KSI	Net Fracture Stress(1) KSI	Notch Strength(2) KSI	β (3)	Critical Crack Index(4) In.	Kc (5) KSI$\sqrt{In}$	Gc (6) + In-lbs/in^2
20	900	1			133				
		"			134				
		10	239	291	130	4.70	0.189	184	1,539
		"	239	272	102	3.28	0.133	154	1,081
30		1	229	195	157	3.85	0.145	154	1,082
		"	229	203	166	4.50	0.169	166	1,265
		"	229	185	157	3.51	0.132	147	988
		"	229	221	153	4.90	0.185	175	1,389
		1 3/4	240	199	159	3.70	0.138	158	1,134
					152				
		10	242	241	133	4.21	0.158	171	1,323
		"	242	255	152	5.59	0.205	194	1,718
40		1	254	265	166	5.43	0.201	202	1,848
		"	254	261	171	5.25	0.192	197	1,771
		"	254	226	168	4.36	0.160	180	1,472
		1 3/4	245	233	165	4.83	0.178	183	1,529
		"	245	205	172	4.05	0.144	165	1,236
		10	238	237	145	4.99	0.183	180	1,478
			238	260	148	5.88	0.212	194	1,712
50		1	243	218	172	4.70	0.174	180	1,464
		"	243	237	176	5.35	0.201	193	1,695
		"	243	257	167	5.81	0.214	199	1,808
		1 3/4	237	222	175	5.30	0.197	187	1,582
		"	237	245	173	6.48	0.243	207	1,952
		10	243	193	136	3.16	0.118	148	993
	↓	"	243	235	133	4.13	0.153	169	1,292

* Allegheny Heat No. 23825

\+ Centrally notched, fatigue cracked specimen

** All specimens refrigerated at - 110°F/16 Hrs.

*** Specimens tore through pinhole

Table 126

EFFECT OF COLD WORK AND MARAGING PARAMETERS ON TRANSVERSE FRACTURE TOUGHNESS OF 25% NICKEL ALLOY*

% Reduction	Maraging** Temp. °F	Maraging Time Hrs.	0.2% Yield Str. KSI	Net Fracture Stress (1) KSI	Notch Strength (2) KSI	β (3)	Critical Crack Index (4) In.	Kc (5) KSI$\sqrt{In}$	Gc (6)+ In-lbs/In^2
20	900	3	243	112	74.7	0.82	0.032	77.3	271
		"	243	107	70.4	0.76	0.030	74.5	252
		10	239	129	101.4	1.31	0.052	96.4	422
		"	239	105	86.2	0.86	0.034	77.8	275
30		3	241	112	73.8	0.91	0.034	78.6	281
		"	241	109	66.6	0.80	0.029	73.3	244
		10	242	113	88.1	1.03	0.039	83.5	317
		"	242	114	81.0	0.99	0.037	82.2	307
40		3	262	97	75.4	0.64	0.024	71.2	231
		"	262	93	69.4	0.57	0.021	66.9	204
		10	238	106	69.5	0.82	0.030	73.6	246
50		3	266	101	73.1	0.59	0.022	70.2	224
		"	266	114	89.6	0.85	0.032	83.8	319
		10	249	110	75.6	0.85	0.031	78.0	277
		"	249	107	83.0	0.85	0.032	78.3	279

* Allegheny Heat No. 23825

\+ Centrally notched, fatigue cracked specimen

** All specimens refrigerated - 110°F/16 hrs.

TABLE 127

HEAT TREAT RESPONSE OF A THICK SECTION** OF
25% NICKEL ALLOY*

Specimen Location In Cube***	UTS KSI	0.2% Yield Str. KSI	Elong. %	Red. In **** Area %
Surface	165	+	+	+
	235	+	+	+
Center	261	246	0++	3.4++
	195	+	+	+

* Allegheny Heat No. 23825

** Cube Dimensions: 4½" x 4½" x 5¼"

*** Specimens machined parallel to flow lines at both locations.

**** H.T. : Soln.: 1450°F/1 hr.
Ausage: 1200°F/4 hrs.
Refrig.: -110°F/16 hrs.
Marage: 900°F/3 hrs.

(1 hr/in. thickness allowed at respective temperatures)

\+ Broke in threads

++ Broke outside gage length

TABLE 128

EFFECT OF FORGING REDUCTION ON THE PROPERTIES OF 25% NICKEL ALLOY

Location	% Reduction	Heat Treatment	U.T.S. (KSI)	0.2% Y.S. (KSI)	% Elong.	% R.A.
Billet						
Vertical-Center	0	1450°F/½ hr.	304.6	256.6	8	29.3
Vertical-Edge	0	1200°F/4 hrs.	303.8	261.6	6.5	5.2
Horizontal-Center	0	-110°F/16 hrs.	257.5	Broke in Threads		
Horizontal-Edge	0	900°F/3 hrs.	296.2	238.2	3	2
First Upset						
Vertical-Center	33.8		235.4	189.9	5	10.9
Vertical-Edge	33.8		248.5	182.9	7	29.2
Horizontal-Center	33.8		233	185.9	5	21.1
Horizontal-Edge	33.8		251.5	205.8	9	32.4
Second Upset						
Vertical-Center	50		231.3	182.4	8	25.3
Vertical-Edge	50		239.2	188.6	9	27.4
Horizontal-Center	50		243.3	200.8	6	22.3
Horizontal-Edge	50		254.9	218.7	7	41.7
Fourth Upset						
Vertical-Center	75		247.7	246.5	3.4	4.1
Vertical-Edge	75		277.6	245.1	3.5	6.3
Horizontal-Center	75		240.2	204.8	6	23.1
Horizontal-Edge	75		Not Machined			
Fifth Upset						
Vertical-Center	84		147.2		1.3	4.4
Circumference	84		235.9	187.9	14	50.3
Horizontal-Center	84		232.2	201.8	7	27.8

Table 129

Critical Fracture Toughness Parameters of 25% Nickel Alloy*

Condition	Heat Treat	N.T.S. KSI	K_{1C} KSI $\sqrt{in}$	G_{1C} ** in-lbs/in^2	N.T.S. / U.T.S.
Annealed	Sol'n: 1450°F/½ Hr.	240	49.6	112.0	.98
	Ausage: 1200°F/4 H.	225	46.6	98.7	.92
	Refrig: -100°F/16 H.	212	43.8	87.5	.87
	Marage: 900°F/3 Hrs.				
40% Cold Work	Refrig: -100°F/16 Hrs	369	76.3	264.2	1.38
	Maragd 900°F /1 Hr.	351	72.6	239.7	1.31
		329	68.0	210.1	1.23
50% Cold Work		344	71.2	230.3	1.30
		353	73.0	242.1	1.33
		322	66.9	203.5	1.22

* Allegheny Heat No. 23825

** Critical fracture toughness calculated from circumferentially-notched tensile bars (K_t = 10)

Table 130

WELD HARDNESS DATA - DPH (1)
25% NICKEL ALLOY - VERTICAL TRAVERSES (2)

Filler Wire Conditions (3)	250 KSI (7C-055)		Mod 20% Ni (7C-058)		Mod 20% Ni + Mo (7C-059)		20% Ni + Mo (7C-060)	
Distance from Top of Weld In.	As-Welded	Aged	As-Welded	Aged	As-Welded	Aged	As-Welded	Aged
.020	321	517	332	540	324	515	304	521
.040	317	538	314	525	331	511	291	529
.060	317	517	310	525	321	511	291	531
.080	325	513	307	521	324	507	286	519
.100	294	525	313	533	271	538	251	533
.120	270	527	279	562	258	560	256	533
.140	261	533	265	562	258	565	258	553
.160	269	551	261	565	276	571	267	565
.180	267	565	256	560	264	574	282	548
.200	--	538	274	555	270	555	264	542
.220	--	--	273	558	276	562	--	--
Average-DPH	293.3	533.4	289.4	546.0	288.4	542.6	275.0	537.4
Rc (Converted)	29.1	51.3	29.7	52.0	28.6	51.9	26.7	51.5

(1) Diamond Pyramid Hardness - 10 KG load, 136° apex angle

(2) Vertical traverse - top to bottom along weld centerline

(3) Aged: 1300°F/4 hrs., air cool, refrigerated 16 hrs. at - 110°F, 850°F/4 hrs.

Table 131

WELD HEAT AFFECTED ZONE HARDNESS DATA - DPH (1)
25% NICKEL ALLOYS - HORIZONTAL TRAVERSE (2)

Base Material	Condition (3)	.015	.030	.045	.060	.075	.090	.105	.120	.135	.150	.165	.180	.195	.210	.225	.240	.255	.270	.295	.320	.345	.370	.395	.420	.445
		Distance From Weld Interface - in.																								
Solution Heat Treated	As-Welded	288	303	260	293	248	218	218	229	230	215	217	219	221	229	235	227	233	236	242	236	236	222	220	-	-
		247	238	230	218	212	214	213	240	233	233	228	238	250	255	251	242	234	200	192	176	189	200	-	-	-
		258	211	197	213	218	212	226	208	223	220	221	210	195	-	206	-	230	-	211	-	-	-	-	-	-
		230	243	203	194	201	174	184	179	177	185	187	203	187	187	189	-	193	-	195	194	196	-	-	-	-
	Aged	551	555	546	551	560	558	555	551	533	529	527	531	529	555	-	553	-	551	553	5[illegible]	-	-	-	-	-
		558	542	546	533	527	531	531	529	521	530	542	579	-	591	-	598	-	603	583	-	-	-	-	-	-
		542	536	535	538	529	542	538	529	542	538	531	527	533	531	542	-	535	-	544	544	544	-	-	-	-
		540	555	542	548	-	533	542	546	560	563	-	588	-	593	-	588	-	-	-	-	-	-	-	-	-
30% Cold Worked	As-Welded	225	211	220	208	197	223	247	262	292	264	290	313	309	299	343	343	-	348	366	377	408	331	343	365	354
	Aged	563	565	538	558	560	542	553	-	565	-	578	-	586	-	609	-	591	574	588	572	572	-	-	-	-

(1) Diamond Pyramid Hardness, 10KG load, 136° apex angle
(2) Traverse taken along sheet centerline
(3) Aged: 1300°F/4 hrs. + Ref. -110°F/16 hrs. + 850°F/4 hrs.

Table 132

TRANSVERSE WELD TENSILE PROPERTIES
25% NICKEL ALLOY SOLUTION HEAT TREATED 0.40" SHEET (1)

Filler Wire		Ausage (2)		Marage						Average Properties					
Type	Heat No.	Temp. °F	Time Hrs.	Temp. °F	Time Hr.	U.T.S. KSI	0.2% Y.S. KSI	Elong. %	R.A. %	U.T.S KSI	0.2% Y.S KSI	Elong. %	R.A. %	Joint Eff-% T.S.	Joint Eff-% Y.S.
250 KSI	7C-055	1300	4	850	4	253	248	1.6	12.0	254	251	1.9	11.5	93	96
						254	254	2.2	11.0						
		1200	4	900	3	236 (3)	219	3.5	8.4	233	216	3.3	8.9	81	81
						230 (3)	212	3.0	9.4						
300 KSI	7C-054	1200	4	900	3	234	215	3.0	6.0	231	216	2.8	5.8	80	81
						227 (3)	217	2.5	5.6						
Mod. 20%Ni	7C-058	[illegible]	4	850	4	237	222	6.0	18.0	247	236	3.9	16.5	90	90
						256	245	1.8	15.0						
		1200	4	900	3	236 (3)	217	2.0	6.9	230	217	2.0	6.6	80	79
						223 (3)	207	2.0	6.2						
Mod. 20%Ni-Mo	7C-059	1300	4	850	4	270	270	1.2	14.0	264	264	1.3	12.5	97	101
						257	257	1.4	11.0						
		1200	4	900	3	241 (3)	235	2.0	4.4	241	235	2.0	4.4	34	88
20%Ni+Mo	7C-060	1300	4	850	4	258	255	1.5	8.0	261	255	1.6	6.5	96	98
						264	256	1.7	5.0						
		1200	4	900	3	242	226	2.0	7.2	247	228	2.5	7.7	86	85
						252 (3)	230	3.0	8.2						

(1) Sheet rolling direction parallel to orientation of specimen axis.
(2) All specimens refrigerated after ausaging: 16 hours at -110°F.
(3) Failed in weld through cover pass and heat affected zone of fusion pass.
All other specimens failed in weld.

Table 134

TRANSVERSE WELD FRACTURE TOUGHNESS PROPERTIES
25% NICKEL ALLOY - 0.140" SHEET

Filler Wire Type	Filler Wire Heat No.	Marage (1) Temp °F	Marage (1) Time hrs.	.2% Yield Str. KSI	Net Fracture Stress KSI	Notch Strength KSI	β	Critical Crack Index in.	K_c KSI $\sqrt{in}$	Gc in-lb/in^2
300 KSI	7C-054	900	3	216	252.7	142.7	6.05	.22	180.9	1488
				216	178	135.3	3.94	.13	138.9	876.9
250 KSI	7C-055	900	3	216	178	135.3	3.94	.13	138.9	876.9
				216	202.3	172.5	5.62	.20	170.5	1322
Mod 20% Ni	7C-058	900	3	212	120.4	117.6	1.55	.059	91.5	380.4
Mod 20% Ni + Mo	7C-059	900	3	235	216.4	122.7	3.48	.14	153.2	1066
				235	177.1	108.5	2.30	.083	120.3	658
20% Ni + Mo	7C-060	900	3	228	247.7	147.9	5.2	.223	191.0	1658
				228	213.1	109	2.9	.114	136.2	843

(1) Preceded by ausage 1200°F/4 hrs + refrigeration -110°F/16 hrs.

Table 135

COMPARISON OF FILLER WIRES
TRANSVERSE WELD TENSILE AND FRACTURE TOUGHNESS PROPERTIES
25% NICKEL ALLOY

Base Material		Filler Wire		Ausage (1)		Marage		Average Weld Properties							Unwelded Sheet Properties					
Condition	Thickness in.	Type	Heat No.	Temp. °F	Time Hrs.	Temp. °F	Time Hrs.	U.T.S. KSI	0.2% Y.S. KSI	Elong. %	R.A. %	Joint Efficiency-% TS	Joint Efficiency-% Y.S.	K_c KSI $\sqrt{in}$	UTS KSI	0.2% Y.S. KSI	Elong. %	RA %	K_c - KSI $\sqrt{in}$ Longitudinal	K_c - KSI $\sqrt{in}$ Transverse
Solution Heat Treated (2)	0.140	250 KSI	7C-055	1300	4	850	4	254	251	1.9	11.5	93	96	-	273	262	-	-	95-150	61-73
				1200	4	900	3	233(4)	216	3.3	8.9	81	81	140-171	288	267	8	35	160-216	38-140
		300 KSI	7C-054	1200	4	900	3	231(4)	216	2.8	5.8	80	81	140-181						
		Mod. 20% Ni	7C-058	1300	4	850	4	247	236	3.9	16.5	90	90	-						
				1200	4	900	3	230(4)	212	2.0	6.6	80	79	91.5						
		Mod. 20% Ni + Mo	7C-059	1300	4	850	4	264	264	1.3	12.5	97	101	-						
				1200	4	900	3	241(4)	235	2.0	4.4	84	86	120-153						
		20% Ni + Mo	7C-060	1300	4	850	4	261	256	1.6	6.5	96	98	-						
				1200	4	900	3	247(4)	228	2.5	7.7	86	85	136-191						
30% Cold Worked (3)	0.140	300 KSI	7C-054	-	-	900	1	223	197	1.8	10.8	84	86	-	266	230	5.5	59	180-199	70-85
		Mod. 20% Ni + Mo	7C-059	-	-	900	1	223	1 7	2.3	11.9	84	86	-						
		20% Ni + Mo	7C-060	-	-	900	1	218	183	2.0	13.1	82	80	-						
Solution Heat Treated (2)	0.070	300 KSI	7C-054	1200	4	900	3	217(5)	202	1.3	6.6	75	76	-						
		Mod. 20% Ni + Mo	7C-059	1200	4	900	3	228(5)	207	1.3	12.3	79	78	-						
		20% Ni + Mo	7C-060	1200	4	900	3	211(5)	183	1.8	14.3	73	69	-						

(1) All specimens refrigerated after ausaging: 16 hours at -110°F
(2) Unwelded sheet solution heat treated 1450°F/1 hour
(3) Refrigerated -110°F/16 hours prior to maraging
(4) Specimens failed in weld and heat affected zone
(5) Specimens failed in heat affected zone

4.0 CURRENT AND FUTURE WORK

The work accomplished under this contract has verified the exceptional capabilities of the maraging steels. This section of the report is concerned with the objectives that future efforts should be directed toward. The proven performance of the maraging steels, and in particular, the 18% Nickel alloys, make the material readily programmed for development. The following paragraphs are development areas which the Curtiss-Wright Corporation believes are imminently the most important for advancing the maraging steel "state-of-the-art".

4.1 Construction and Test of Full Scale Motor Cases

To date, numerous evaluation programs on material representative of commercial size heats have been performed by industry. The 18% Nickel alloys have been proven to possess the outstanding strength and toughness sought for solid rocket motor casings. The Curtiss-Wright Corporation has conducted subscale evaluation of casings with excellent results. Bursts as high as 349 KSI have been achieved with 6" I.D. subscale vessels. At present, the Corporation has constructed two full scale, Pershing type (40" I.D.) motor cases. These cases are currently undergoing test. Preliminary data from the testing of two 6" I.D. subscale vessels representing the same heats of material in the Pershing cases are partially analyzed. The results, based on PR/t show both subscale vessels to have burst at approximately 345 KSI. If, as all current and past data indicates, the proof and burst tests of the full scale Pershing reproduce subscale performance, maraging steels will have passed into the production phase of application.

4.2 Solid Rocket Booster Motor Casings

Large NOVA type booster cases demand extremely dependable material performance. Unfortunately, the associated problems are compounded by the material mass and mill product sizes involved in construction. Depending on the case diameter under development, plate gages of 0.300" to 1.0" must be fabricated to the same stringent strength and toughness requirements as missile motor casings.

Realizing the urgent need for material development in the booster case area and being aware of the potential of maraging steels for this application, the Aeronautical Systems Division, Wright-Patterson AFB has initiated further development.

A contract for the evaluation of maraging steels for large diameter booster case application has been awarded to the Aerojet General Corporation. The work performed under this contract will be directed toward the evaluation of maraging steel plate in base metal and welded

form. Strength and toughness capabilities will be established to gage the performance of the alloys in thick plate sizes representative of large heats. This work will serve as the initial step in the development of the alloys for booster case construction.

4.3 Process Development of Maraging Steel Forgings.

The area of raw material consistency and forging reproducibility from heat to heat of material would remain intangible unless a program were specifically initiated to develop statistically sound data. The Aeronautical Systems Division, Wright-Patterson AFB has requested contractor comments regarding interest and proposed program plan. This contractor has replied affirmatively as follows:

The scope of this program should be inclusive of all factors in fabrication since forging operations are dependent upon numerous parameters. Forging properties, including strength and toughness, as a function of directionality, should be determined by a systematic analysis of alloy melting method, chemical composition, billet conditioning, degree of forging reduction, start and finish forge temperature and die preheat temperature. Because of the large number of variables involved in such a program and the cost of the large size heats which must be used to produce meaningful data, a statistical approach should be used in data collection and generation in order to obtain maximum information at minimum cost. By means of an initial approach to obtain the relative significance of each variable and variable interactions, a more efficient study of pre-forging and forging variables will be possible. After the relative significance of variables is determined, the important preforging parameters should be initially set apart from forging parameters thereby reducing the number of dependent variables. Preforging parameters should be evaluated in detail regarding the reproducibility of properties within heats, between heats and as a function of heat size. The effect of billet conditioning must also be included since final forging properties are known to be highly dependent upon this factor. The evaluation should be made on as large a sample size as possible. Different material suppliers should be surveyed for the collation of available data to supplement this program and complement the data generated. Having established preforging parameters, a second phase of the program would evaluate forging parameters still using a statistical approach. Forging parameters can be evaluated by combining the findings from preforging studies. The design of this phase must be inclusive of all forging variables since individually, they do affect the forged product. Generally, the program must evaluate on an all inclusive scale the variation in forgings as a function of heat size, composition, and melt method as well as billet conditioning and subsequent degree of reduction and forging schedule employed.

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